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Preface

This study was designed to evaluate the effectiveness of aftermarket fuel delivery systems for vehicles fueled by compressed natural gas (CNG) and liquefied petroleum gas (LPG). Most of the CNG and LPG vehicles studied were converted to the alternative fuel after purchase. There are wide variations in the quality of the conversion hardware and the installation. This leads to questions about the overall quality of the converted vehicles, in terms of emissions, safety, and performance. There is a considerable body of emissions data for converted light-duty vehicles, and a smaller amount for medium- and heavy-duty vehicles. However, very few of these data involve real world conditions, and there is growing concern about in-use emissions. This report also attempts to assess factors that could allow in-use emissions to vary from the "best-case" results normally reported. The study also addresses issues of fuel supply, fuel composition, performance, safety, and warranty waivers. The report is based on an extensive literature and product survey and on the author's experience with fuel delivery systems for light-duty vehicles.

I would like to thank several people for their contributions to the project. Mr. Bradley Cohen assisted with the literature research. Several professionals contributed their valuable time to review the draft report: Charles White of NREL (retired from Cummins Engine Company), William Liss of the Gas Research Institute, Alan Wells of the Gas Research Institute, and Jeff Wilson of the California Air Resources Board. It should be understood that remaining errors of fact or interpretation are entirely my own. Finally, a special note of thanks is reserved for Mr. Brent Bailey, the project monitor at the National Renewable Energy Laboratory, for his encouragement and patience.

Executive Summary

A study was undertaken to evaluate the effectiveness of aftermarket fuel delivery systems for compressed natural gas (CNG) and liquefied petroleum gas (LPG). This involved a detailed literature and product review to evaluate the performance, emissions, drivability, and safety of vehicles fueled by CNG or LPG.

Currently, there are more than 500,000 LPG vehicles and 35,000 CNG vehicles in the United States. Most of these are light-duty vehicles, and most demonstrate reliable, economical operation. Under closely controlled conditions, these vehicles can also demonstrate low levels of exhaust emissions. However, there is reason to believe that the emissions from in-use vehicles may be higher. Conclusions drawn from the study are summarized below.

Light-duty Vehicles

- Emissions of carbon monoxide (CO) and reactive hydrocarbons (HC) are typically lower with CNG and LPG. Nitrogen oxide (NO_x) levels are somewhat inconclusive. Total HC emissions may be higher, particularly with CNG.

- The composition of LPG and CNG is variable. CNG variations result from the blending of thousands of individual producer wells in the pipeline network. Significant variation can also occur within the local distribution network through the use of propane/air peakshaving. LPG variations are attributable to source composition (if produced from natural gas), or the refinery balance, if produced during the refining of petroleum.

- The air/fuel (A/F) ratio of gaseous-fueled engines equipped with catalytic converters should remain within 0.5%-1.0% of stoichiometric. This is difficult when the Wobbe index (an index of fuel delivery rate) of the fuel may vary by 10% because of composition variation.

- Most fuel metering systems in use are purely mechanical, with no feedback to correct for variations in environment and fuel composition. Purely mechanical systems can exhibit wide variations in emissions levels as fuel composition changes. An improvement over purely mechanical systems is the addition of oxygen feedback. This ensures stoichiometric operation, even when fuel composition varies. Computerized fuel metering systems with exhaust oxygen feedback and adaptive learning capabilities will be available in significant quantities in late 1992.

- The vehicle itself is a major factor in the effectiveness of a fuel delivery system. Conversion of a carbureted vehicle to dual-fuel operation may result in high HC emissions (from evaporative losses) and reduced power (resulting from the use of manifold heating). Conversion of a fuel-injected vehicle has its own set of difficulties, arising from interference from the on-board computer's emission control functions (canister purge and exhaust gas recirculation [EGR]) and on-board diagnostics (knock, oxygen [O_2], acceleration enrichment, and deceleration enleanment).

- Most CNG and LPG emissions data are from specially prepared vehicles. Although this demonstrates the potential of the fuel, it is not indicative of emissions from the in-use fleet. Currently, data on the in-use emissions of gaseous-fueled vehicles operating on fuels of varying composition are not available.

Medium- and Heavy-duty Vehicles

Additional factors influencing the emissions from medium- and heavy-duty vehicles include:

- HC emissions from medium- and heavy-duty vehicles may be high, and are primarily attributable to fuel loss during the scavenging process (in two-stroke cycle engines) and during the exhaust/intake overlap period (in four-stroke cycle engines).

- Variations in A/F ratio from cylinder to cylinder can be a major problem for fumigated gas engines.

- Diesel pilot and lean-burn systems must currently operate "open loop," which is difficult with fuels of varying composition. Lean-burn sensors appear poised for widespread use within a few years, which should help with this issue.

- Data on in-use emissions of medium- and heavy-duty vehicles are scarce.

Performance

- The theoretical power loss from the displacement of engine air with a gaseous fuel is ≈9.4% for natural gas and ≈4% for LPG. If a heated intake manifold is used (typical in the conversion of a gasoline vehicle), the loss may be even greater. In-use data for natural gas shows a considerable variation in power loss, from the theoretical 9.5% to as high as 20.0%.

- Increased compression ratio and turbocharging can both be used to help offset the power loss from gaseous fuels, but neither is suitable for widespread use in vehicle conversions.

- There is information to suggest that drivers may be more influenced by the responsiveness of a vehicle to throttle transients than by the overall loss of power at wide open throttle that is typical of gaseous fuels.

- No systematic studies have been conducted to quantify cold starting, hot starting, or drivability. The automotive industry has developed standard tests to assess these factors on production vehicles.

Safety

- The safety of converted vehicles is strongly related to the quality of workmanship of the conversion.

- References to LPG vehicle fires appeared in the literature, and were attributed to poor workmanship. No mention of CNG vehicle fires was discovered, although CNG vehicles represent a smaller sample. A reported worldwide search could not find a single instance of a U.S. Department of Transportation (DOT)-approved cylinder failing in a CNG vehicle application.

- Although the industry has focused on the impregnability of high-pressure tanks (both CNG and LPG), the gas lines, hoses, and valves remain the weak links in an accident.

- Only a few states have certification requirements for conversion equipment, although various groups are proposing industry standards.

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Introduction

Currently there are approximately 700,000 CNG vehicles and 2,500,000 LPG vehicles in use worldwide. A breakdown of their locations is given in Table 1[1].

Table 1. Estimated Worldwide Distribution of CNG and LPG Vehicles (composite)

Country	CNG	LPG
Italy	300,000	
Australia		200,000
New Zealand	125,000	50,000
Canada	20,000	140,000
Argentina	15,000	
Mexico		435,000
Netherlands		700,000
Korea		160,000
Soviet Union	20,000	
United States	35,000	500,000
Worldwide	**700,000**	**2,500,000**

Information on the growth of CNG and LPG markets in North America is given in Table 2.

Table 2. Estimated North American LPG and CNG Markets (composite)

	U.S.	Canada
LPG growth (conversion/year)	25,000+	15,000 - 25,000
CNG growth (conversion/year)	1,500 - 10,000	4,000

With the exception of a few thousand "quasi-production" vehicles, all these vehicles were converted to alternative fuels with aftermarket equipment. Some of this equipment has been very effective and reliable, but some has not fulfilled the potential of the fuel for safe, clean, and reliable operation. Although considerable attention is currently being focused on the development of new technologies for dedicated CNG and LPG engines and vehicles, aftermarket conversions will continue to play a strong role in the near future. Therefore, this study was conducted to evaluate the current state of technology for converting spark ignition and compression ignition engines for CNG and LPG service. A goal of this study was to identify shortcomings in the technology with regard to safety, emission control, and drivability, and to target future research and development needs.

[1]Note - these estimates vary widely, based on the source.

The Literature Survey

A literature survey was conducted to determine the state of the art of aftermarket fuel delivery systems. The literature survey uncovered references to

≈250 relevant titles from a search through Compendex and other engineering indexes
≈200 relevant titles from searches of engineering indexes on CD-ROM
≈100 references from ancillary sources:
- American Gas Association (AGA)
- Gas Research Institute (GRI)
- LP Gas Clean Fuels Coalition

≈50 miscellaneous titles including:
- Conference preprints
- Vendor materials
- Data from industry groups and testing laboratories.

Approximately 400 of these references were procured for examination, with 190 of them included in the final bibliography (see Appendix A). Approximately two-thirds of these sources provided information used directly in the project. The remainder was retained in the bibliography for background.

Emissions Data

A collection of emissions results for light-duty vehicles is presented in Appendix B. Heavy-duty emissions are presented in Appendix C. An examination of all the data reveals a tremendous amount of spread in the information. When examining these data, it should be noted that these results contain an inherent bias. Many of the vehicles have been specially "tuned" for low emissions. Very little data exist for in-use vehicles. The Colorado Department of Health (CHD) is conducting a study of the emissions from in-use alternative-fueled vehicles. This report should be released in 1992.

Supply Issues

Discussions about the relative merits of CNG and LPG presume adequate supplies of both in the near term. Unconventional sources and new production technologies contribute to abundant supplies of natural gas. In contrast, LPG has recently been relegated to a secondary role because of concerns about long-term supplies. Recent analyses seem to indicate that LPG is available in sufficient quantities to allow its role to be expanded in the North American market.

Natural Gas

Natural gas estimates are notoriously inaccurate. Current estimates of U.S. natural gas reserves range from a low estimate of 35 years [U.S. Geological Survey (USGS) estimate reported in Ker89] to a commonly cited estimate of 100+ year reserves [AGA91d]. Historically, natural gas production has been a by-product of oil production, so the more conservative natural gas estimates have been related to estimates of domestic oil reserves, which are declining [Ker89]. Natural gas is commonly found in oil-producing formations, but is also found in potentially large quantities in formations where oil is not found, and which therefore have not been previously explored. In light of the increasing importance of natural gas, these sources of "unconventional" gas are now being actively explored. Estimates of conventional and unconventional reserves are given in Table 3.

Table 3. Unconventional Sources of Natural Gas in the United States

	Total Resource Base	Source
Conventional gas		
Lower 48 states, 1988 Department of Energy (DOE) estimate	29.7 TCM[2]	[Mac90, BB89]
Conventional gas, 50 states, Potential Gas Committee	20.9 TCM	[Mac90]
1988 USGS estimate	16.1 TCM	[Ker89]
Coal seam gas		
Estimated resource	70.0 TCM	[Mac90]
Recoverable @ $7.50/thousand cubic feet (mcf)	10.0 TCM	[Mac90]
Recoverable w/current technology	1.4 TCM	[BB89]
Recoverable from seams <1500 m	2.0 TCM	[Ned88]
Eastern shales		
Estimated resource	17.0 TCM	[Mac90]
Recoverable @ $7.50/mcf	1.0 TCM	[Mac90]
Feasible recovery	1.0 TCM	[Ned88, BB89]
U.S. tight sands		
Resource	17.0 TCM	[Mac90]
Recoverable @ $7.50/mcf	5.0 TCM	[Mac90]
Recoverable U.S. gas	14.0 TCM	[Ned88]
Recoverable w/current technology	5.0 TCM	[BB89]
Coal seams		
Estimated resource	70.0 TCM	[Mac90]
Recoverable @ $7.50/mcf	10.0 TCM	[Mac90]
Geopressurized aquifers		
Estimated resource	85.0 - 2800.0	[Mac90]
USGS estimate	160.0 TCM	[Ned88]
Methane clathrates/hydrates		
In North American permafrost (primarily Alaska)	96.0 TCM	[Mac90]
Annual U.S. gas usage	0.5 TCM	1988 Annual Energy Review

Note that these figures indicate tremendous reserves in unconventional sources. Methane clathrates have not been included in estimates of gas resources to date as this is a relatively unexplored resource. Clathrates are icelike compounds in which methane and other gases are trapped in a cubic lattice structure of ice crystals. Clathrates are found at shallow depths in the permafrost regions, and on the continental shelf in potentially huge quantities. Worldwide, MacDonald [Mac90] estimates the total global resource of natural gas as 21,000 TCM, with an energy content of 8×10^{23} Joules (J). This is more than five times the energy content of coal resources, which is estimated at 1.5×10^{23} J. Methane hydrates are similar to clathrates, and are conservatively estimated at 100 TCM worldwide [Ned88].

[2] TCM - trillion cubic meters.

LPG

A common perception is that LPG is not available in sufficient quantities to play a major long-term role: "Propane is also a very clean fuel, but is currently available mostly as a by-product from gas and oil, and is expected to be very limited in supply as compared to natural gas." [Bec90]. The LPG industry argues in [Web89, WD91] that the domestic LPG supply is sufficient to economically supply 21 million vehicles in 2005 — 12.5% of U.S. automobiles. Projections by the California Energy Commission (CEC) (see Table 4) indicate that both CNG and LPG can be expected to remain attractively priced in the near future. About 70% of the U.S. production of LPG is extracted from natural gas, with the remainder produced during the refining of crude oil. Approximately 15% of the current supply is imported. Supplies are not anticipated to be a problem in the 1993-2000 time frame [CEC89], and propane proponents suggest that LPG could fuel 6.5 million vehicles in 2004 without severely affecting domestic supplies [Web89]. Proponents argue that in the more distant future, stable LPG supplies can be assured from switching propane from its use as a feedstock to use as a motor fuel, and by expanding the production of LPG from natural gas.

Table 4. California Energy Commission Projections of Fuel Prices [CEC89]

	Gasoline (prem. unleaded) $/gal equiv.	Natural Gas $/gal equiv.	LPG $/gal equiv.
Projected 1993 Fuel Prices			
Wholesale	0.77	0.31	0.42
Retail	1.21	0.71	0.88
Projected 2000 Fuel Prices			
Wholesale	0.93	0.38	0.52
Retail	1.39	0.84	0.98

Emissions Formation

Environmental concerns are an important part of the driving force behind renewed government interest in alternative fuels. California is the most proactive state in establishing stringent vehicle emission standards. The new California standards for light-duty vehicles are listed in Table 5. Currently, alternative-fueled vehicles appear to have an edge in meeting these standards. Both CNG and LPG vehicles have demonstrated the ability to meet the stringent ultra low-emission vehicle (ULEV) requirements in isolated, well-tuned vehicles.

Table 5. Proposed California Vehicle Exhaust Emissions Standards for Light-duty Vehicles

	Exhaust Emissions, g/mi		
Vehicle Category	NMOG	CO	NO_x
Transitional low-emission vehicle (TLEV)	0.125	3.4	0.40
Low-emission vehicle (LEV)	0.075	3.4	0.20
ULEV	0.040	1.7	0.20

Durbin [Dur89] presents an excellent overview of steady-state emissions from gaseous-fueled engines (primarily natural gas), although his document does not address the question of control systems. Parametric tests conducted at Southwest Research Institute [DF87] clearly demonstrate several trends:

***Ignition Timing*.** Increasing ignition timing has a marked effect on BSFC and NO_x, reducing BSFC and increasing NO_x. Ignition timing has a relatively minor effect on HC and CO.

***Engine Load*.** Increasing load increases NO_x, reduces BSFC, and decreases HC. Engine load does not have a marked effect on CO.

***Air/Fuel (A/F)*.** Increasing A/F ratio (assuming operation on the *lean* side of the NO_x peak) reduces NO_x, but may increase HC. Increased air has little impact on CO, but may cause an increase in fuel consumption as misfire conditions are approached.

***Manifold Temperature*.** Decreasing manifold temperature by 35°F (20°C), from 110°F to 75°F, decreased NO_x by 27% but increased HC by 30%. Fuel consumption increased by approximately 10% and the carbon monoxide remained stable over this range.

Carbon Monoxide

Carbon monoxide formation is generally considered to be a bulk phase phenomena [Dur89]. CO is part of the equilibrium relation in the water-gas relationship; its formation is enhanced by decreasing O_2 concentration. Even engines that are stoichiometric overall may have rich cylinders because of cylinder-to-cylinder maldistribution. In a lean-burn engine, CO may be produced from the quenching of the fuel mixture against the cylinder wall [Kli90, Hey88]. In general, CO emissions from CNG and LPG are quite low.

Hydrocarbons

The issue of hydrocarbon emissions is complex. More than 350 different HC species have been identified in engine exhaust streams. The primary source of HC emissions are from wall quenching and from the gas trapped in the region above the top land between the piston and cylinder wall [Kli90, Hey88]. Because of the high ignition temperature of the methane in natural gas, methane emissions can be expected to be high. Unfortunately, methane, and to a lesser extent propane, is a stable molecule, and is not readily oxidized in catalytic converters designed for use with gasoline. HC emissions from LPG can be expected to lie between those for natural gas and those for gasoline. Propane is more reactive than methane, but less reactive than gasoline.

Another important source of HC occurs with dual-fuel natural gas/gasoline and LPG/gasoline vehicles. On dual-fuel vehicles, the gasoline system purges the gasoline fumes contained in the charcoal storage canister through the engine. This can be a significant source of HC emissions, and can cause poor idle quality and rich misfire. On computer-controlled vehicles with adaptive learning, the adaptive learning capability may try to respond, resulting in "mis-learning" [Car91, Law91]. At idle, the canister purge can provide 20%-50% of the total fuel requirement. Tests to quantify this effect have indicated that non-methane hydrocarbons (NMHC) may double and CO may increase by 50% because of canister purge [Law91]. These results are reported in Table 6. This situation is applicable to LPG as well as CNG.

Table 6. Effect of Gasoline Canister Purging on HC Emissions

Canister Status	NMHC g/mi	THC g/mi	CO g/mi	NO_x g/mi
No Purge	0.15	0.99	1.7	0.58
Purge (13 Reid vapor pressure (RVP) fuel)	0.31	1.29	2.5	0.59

Even though the total HC emissions from natural gas are higher than from gasoline, the emissions are primarily CH_4 and other paraffins. The paraffins in the exhaust stream of a natural gas vehicle are much less reactive than the olefins and aromatics from gasoline-fueled engines, as demonstrated in Table 7.

Table 7. Hydrocarbon Reactivity of Natural Gas and Gasoline Emissions [in Dur89]

	Paraffins (ppm)	Olefins (ppm)	Aromatics (ppm)	Reactivity Index
Before conversion				
Gasoline	330	195	160	2370
Immediately after conversion				
Gasoline	340	250	200	2940[3]
Natural gas	600	30	15	285[4]
After 4,000 miles				
Gasoline	270	140	155	1855
Natural gas	440	23	2	190

Natural gas emissions contain virtually no particulates, gasoline vapor, benzene, or 1,3 - butadiene, all of which are considered toxins. The Environmental Protection Agency (EPA) estimates that if all U.S. vehicles were operating on natural gas in 2005, deaths from cancers from air toxics would drop from 1,098 cases per year to 47 cases per year [Wea91].

[3]For gasoline, calculated as 1 x (paraffin concentration) + 8 x (olefin concentration) + 3 x (aromatic concentration), reported in [Dur89].

[4]For natural gas, calculated as 0 x (paraffin concentration) + 8 x (olefin concentration) + 3 x (aromatic concentration). Explanation for zero paraffin weighting: "The paraffin component of natural gas exhaust is methane. Methane has zero photochemical reactivity; Therefore, paraffins should be weighted zero in reactivity unit calculation." Reported in [Dur89].

NO_x

NO_x is a mixture of NO and nitrogen dioxide (NO_2[5]) that is formed during the combustion process. The primary constituent is NO, which nominally accounts for ≈90% of the total NO_x concentration. NO_x formation is related to three items: temperature, time, and the availability of oxygen. Variables that tend to reduce peak combustion temperatures (lean combustion, exhaust gas recirculation, and water injection) will reduce NO_x. Reductions of combustion duration (retarded ignition timing) will also reduce NO_x. Finally, increasing oxygen availability through mixture enleanment will *initially* increase NO_x levels, although very lean operation (ϕ[6] = 0.7) lowers NO_x levels. The lean-burn approach to NO_x reduction encompasses two issues. With moderate enleanment ($\phi = 0.9$), the increased oxygen availability dominates the cooling effect, and NO_x levels rise. As the amount of excess air is further increased, the cooling effect dominates and NO_x levels are reduced.

It is possible to use the reaction of NO with a reducing agent such as hydrogen (H_2), ammonia (NH_3), CO or HC. Of these, CO is universally used in vehicle applications[7], although NH_3 has been suggested for stationary engines. It has also been proposed that HC fuels such as methane or propane could be used for the same purpose. This has been demonstrated in a benchtop recirculation reactor [HH76], but apparently not on a vehicle.

Water injection is occasionally proposed to reduce the peak combustion temperature and therefore reduce NO_x. Tests on an industrial natural gas engine verified this effect, but also identified fuel consumption and CO penalties [Sha75]. In the test, 0.4 lb of water per brake horsepower hour (lb/bhp-h) was injected into the engine, reducing NO_x from 7 g/bhp-h to 2 g/bhp-h, a ≈70% reduction. Unfortunately, the use of water injection also produced a 10% increase in fuel consumption, a 10% increase in CO, and a 7% loss of power. Similar effects can probably be expected in CNG- or LPG-fueled vehicle engines.

An interesting concept to reduce NO_x in LPG and LNG engines is to utilize the heat of vaporization to cool the intake charge temperature, thus reducing peak combustion temperatures. A simple calculation based on the heat of vaporization of LPG, the stoichiometric A/F ratio, and the specific heat of air shows that liquid LPG injection would cool the intake charge by 27°C (49°F). This should help to reduce NO_x formation, although HC emissions could rise. Liquid LPG injection is proposed in [Wal89, MH67, WB91], but no test results have been uncovered. This should be a priority for future study. An alternative solution would be to utilize an LPG/air heat exchanger to vaporize the LPG and cool the incoming air.

Cylinder-to-cylinder Mixing

For stoichiometric engines operating on natural gas, the equivalence ratio should be in the narrow region between ϕ = 1.005-1.008, less than a 1% window [Kli87]. Similarly, for lean-burn engines, cylinder-to-cylinder variations of +/- 1% may also be unacceptable [Kli89]. In practice, this level of control is difficult to achieve because of the challenge of accurately metering fuel and the difficulty of ensuring uniform mixing in the engine's intake system. Tests on a GM 7.0-L engine at Southwest

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[5] With small quantities of dinitrogen pentaoxide (N_2O_5) and other nitrogen oxides.

[6] ϕ the equivalence ratio of an engine is non-dimensionalized measure of air/fuel ratio, and is defined as:

$$\phi = \frac{(\mathrm{air/fuel})_{\mathrm{stoichiometric}}}{(\mathrm{air/fuel})_{\mathrm{actual}}} = \frac{(\mathrm{fuel/air})_{\mathrm{actual}}}{(\mathrm{fuel/air})_{\mathrm{stoichiometric}}}$$

[7] Engines that utilize three-way catalysts operate with stoichiometric air/fuel mixtures.

Research Institute (SwRI) have shown that a supposedly stoichiometric engine may exhibit variations in cylinder-to-cylinder distribution as high as 20% [Sny91]. The cylinder distribution problem can be exacerbated in converted diesel engines that normally operate unthrottled and are not designed for high vacuum levels. Under high vacuum conditions, air leakage past valve stem seals may occur. Diesels converted by original equipment manufacturers (OEMs) can utilize special valve stem seals to avoid this problem.

Mixing within the cylinder may also have an effect. Sztenderowicz and Heywood demonstrate that in-cylinder inhomogeneity of a stoichiometric gasoline/air mixture produces a slight increase in the standard deviation of the flame initiation and development, but no significant impact on overall burn duration or indicated mean effective pressure (IMEP) [SH90]. To date, however, similar tests have not been conducted with natural gas mixtures. In an interesting experiment with a constant volume bomb, researchers have shown that combustion was much faster in natural gas mixtures that were allowed to "age" for 10 minutes than in similar "unaged" samples [Wel91], indicating a potential effect from "microscale" mixing.

Air/Fuel Setpoint

Catalyst specialists at the Engelhard Corporation [BCH83] report data that show that stationary natural gas engines should be operated 0.3%-0.5% rich for effective three-way catalysis. The ideal operating temperatures for NO_x reduction are in the range of 900°F to 1100°F (480°C-600°C), which corresponds to the exhaust temperature range for stoichiometric natural gas engines. Under these conditions, field tests have shown 90+% reduction in NO_x levels. The projected life of these catalysts is five to seven years of continuous operation, which corresponds to *more than three million miles of vehicle driving.*[8] The conclusion regarding the benefits of slightly rich operation is confirmed by Klimstra [Kli87], who reports that the optimum A/F setpoint for natural gas vehicle engine is 0.5% - 0.8% rich of stoichiometric. The optimum setpoint for LPG has not been discussed in the literature.

Sensor Response

A recent study funded by the Gas Research Institute [SK91] examined the characteristics of exhaust gas oxygen sensors when they were used with natural gas. The study concluded that the standard zirconia potentiometric sensor is biased to the lean side of stoichiometric, whereas a ≈0.5% rich bias is desired. Another researcher [Kli87] has observed that the standard zirconia sensor gains more of a lean bias as the concentration of highly reactive components, such as hydrogen, is increased. The effect of LPG on oxygen sensor response has not been discussed in the literature.

Agency Studies

The Colorado Department of Health (CDH) performed a study [NR89] that examined the emissions from natural gas vehicles before and after conversion. The vehicles tested were a 1981 Ford van with 5.0-L engine, a 1978 Chevrolet pickup with a 5.7-L engine, a 1984 Chevrolet van with 5.0-L engine, and a 1986 Chevrolet pickup with a 4.3-L engine. All of the vehicles were equipped with Automotive Natural Gas, Inc., (ANGI) CNG conversion kits for dual-fuel operation. The relative results from the Federal Test Procedure (FTP) and Highway Fuel Economy (HFET) test are shown in Table 8.

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[8] It should be noted that vehicle catalysts experience severe temperature cycling from the daily warm-up/cool-down sequencing, and from power variations while driving. During transient vehicle operation (particularly deceleration), periodic enrichment occurs, causing temperature spikes in the catalytic converter. Temperature cycling outside of certain limits can degrade catalyst effectiveness and reduce catalyst life.

Table 8. Changes in CNG and Gasoline (Indolene) Emissions after Conversion to CNG [NR89]

Emission Component	CNG versus Indolene before Conversion	Indolene after Conversion versus Indolene before Conversion
CO, FTP	- 98.4%	+ 19.2%
HC, FTP total	+ 18.6%	+ 16.9%
HC, FTP, reactive	- 30% -70%, estimated	+ 16.9%
NOx, FTP avg.	+7.9%	
NO_x, HFET avg.	-20.4%	
CO_2	-25.6%	+1.7%
Aldehydes, total	-9.6%	
Formaldehyde	+60.4%	
Acetaldehyde	-30.0%	
Acrolein	-67.4%	
Reactivity, estimated	-75%	
Particulates	-53.7%	-5.4%
Fuel Economy, FTP	+5.7%	-3.4%
Fuel Economy, HFET	-11.5%	-3.3%
Peak Horsepower	-24.3%	not available
Peak Torque	-22.5%	not available

As expected, CO levels were greatly reduced when operating on CNG. It should be noted, however, that emission levels on indolene increased after conversion. This is largely due to the fact that the conversion kit may introduce a restriction on the flow of intake air to the engine. All four vehicles tested are believed to be carbureted vehicles, with the carburetor discharge tube located upstream of the throttle plate but downstream of the CNG venturi. This arrangement may be expected to result in a slight vacuum applied to the gasoline metering system, resulting in a richer fuel mixture. It should be noted that the vast majority of new vehicles are now fuel injected, and fuel injection is less sensitive to enrichment from air restriction. In addition, almost all fuel-injected vehicles are equipped with manifold pressure sensing and O_2 feedback, allowing each vehicle to compensate for any restriction of the inlet air.

In a separate document, the EPA has established the following emission factor adjustments for alternative fueled vehicles. These factors, given in Table 9, represent the ratio of an emission component from the alternative fuel to the same component from gasoline. Thus, an adjustment factor below one represents a reduction of emissions, and a factor greater than one represents an increase. Although the EPA recognizes that individual results can be much better than reflected in the allowable adjustment factors, their adjustment factors are felt to represent a "fleet average."

Table 9. EPA Adjustment Factors for CNG Vehicles [EPA88]

Component	Adjustment Factor
HC	0.60
CO	0.50
NO_x	1.40
HC evap.	0.0

The EPA factors reflect the CDH results that CO and reactive HC are reduced with the use of CNG. The NO_x emissions are less certain, however, as NO_x is highly dependent on the accuracy of the A/F metering system. The EPA factor for evaporative HC appears to assume a dedicated CNG vehicle. The evaporative emissions from a dual-fuel vehicle will be substantially the same as from a gasoline-only vehicle.

Temperature Effects

Cold Starting, Cold Operation

Fleming and Allsup [FA71] performed a study on non-catalytically controlled vehicles, which indicated that emissions from natural gas vehicles show almost no sensitivity to ambient temperature in the range 20°F-100°F, while gasoline-fueled vehicles of the same vintage show great sensitivity. This is largely due to the need to provide fuel enrichment for gasoline cold starting. No enrichment is used for natural gas, and fleet operators generally report excellent cold startability. Cold (20°F) weather and hot (105°F) weather testing by the EPA confirm generally stable emissions [GKR90]. In the sub-zero range, there is anecdotal evidence of cold-starting difficulties for both CNG and LPG. Speculations on the cause of this difficulty include ignition failure because of very difficult ionization conditions, and general sluggishness of mechanical components.

Hot Starting

Hot starting can present difficulties for gaseous fueled vehicles. This is believed to be due to "hot-start enleanment," and is most pronounced in warm weather. Both CNG and LPG used coolant-heated regulators. LPG requires heat from the engine coolant to vaporize the fuel. CNG requires the use of a coolant-heated regulator to prevent hydrate formation when high-pressure gas is throttled from high pressure (3,000-3,600 psi) to intermediate pressure (nominally ≈100 psi; varies with system). After an engine is shut down, the engine coolant continues to absorb heat from the engine, raising its temperature. If the vehicle is restarted within a critical period after shutdown (long enough for the coolant temperature to rise, but before the entire system cools), the elevated coolant temperature will heat the gas more than normal, lowering its volumetric heating value and density. A simplified analysis shows that this would result in mixture enleanment.

Exhaust Catalysis

Catalytic converters for natural gas vehicles present a challenge. The primary difficulty is oxidation of exhaust HC. A simple rule of thumb states that the specific rate of HC conversion in a catalyst increases tenfold for each additional carbon atom in the chain [Y. Yao, *Ind. Eng. Chem. Prod. Res. Dev.*, Vol 19(3), 295, 1980, reported in Sum91]. Thus, propane conversion is ≈100 times as fast as methane conversion, and butane conversion is ≈1,000 times faster than methane conversion.

Palladium is preferred over platinum for methane and ethane. Platinum is preferred over palladium for remaining HC [Sum91]. The effect of dispersion in catalysts also appears to be important; methane conversion appears to be favored by relatively dispersed ("chunky") catalyst application, instead of the more intuitive evenly distributed catalyst [Sum91].

The literature appears to be unanimous concerning the difficulties in obtaining effective three-way exhaust catalysis of the lower HC. Catalysis is limited to a more narrow window of A/F than with gasoline. Klimstra [Kli87] molecular weight provides an excellent discussion of the subject that is widely referenced. Klimstra makes the following points:

- The centerline of the window for simultaneous reduction of NO_x, CO, NMHC, and CH_4 occurs 0.5%-1.0% rich of stoichiometric, although the exact location varies with catalyst age.

- The width of the "window" is about 0.5%.

- Catalyst effectiveness degrades with age.

- The standard zirconia O_2 sensors appear to be sensitive to exhaust composition. The sensor is biased in the lean direction by the presence of highly reactive gases, such as H_2 (which is present in the exhaust stream), and is moved in the rich direction by the presence of less reactive gases, such as methane. An excellent discussion of oxygen sensor response is contained in [SK91].

Fuel Composition

Gaseous fuels differ from liquid fuels in their variability and their lack of processing. The composition of CNG and LPG varies according to the origination, processing, and blending of each. This places an additional burden on the fuel control system. Previously discussed studies have shown that effective exhaust catalysis requires air-fuel ratio control of better than 1%. Variations in the composition of gaseous fuels with time and location are such that open loop A/F control within 10% would be difficult. This can have a serious impact on vehicle emissions, and emphasizes the need for closed-loop, feedback control.

CNG Composition

Natural gas is primarily methane, but its exact composition is a mixture of hydrocarbon and inert gases that vary temporally and geographically. The specific composition of natural gas emerging from a pipeline is a function of

- The characteristics of the gas from individual gas wells

- The level of gas processing prior to shipment

- The amount of commingling that occurs during transport

- Local gas modification to control Wobbe index (a measure of relative energy flow through a fixed orifice) or to ensure adequate supply during high demand periods. This may include the use of compressed gas stored in tanks or underground reservoirs, liquefied natural gas, or propane-air mixtures.

Natural gas composition can be varied by processing. In some locations, ethane, propane, butane, and even CO_2 may have sufficient commercial value to warrant their removal for resale. If levels of these gases are higher than allowed by custody transfer agreements, the gas must be "cleaned" regardless of the resale value of the components. The typical contract limits are presented in Table 10.

Table 10. Typical Contract Limits for Custody Transfer of Natural Gases [LT91, from 1971 AGA report and 1984 New York Mercantile Exchange]

Component	Typical Contract Limits (maximum)
Hydrogen sulfide	0.25-1.0 grains/100 ft^3
Mercaptans	1.0-10.0 grains/100ft^3
Total sulfur	10.0-20.0 grains/100 ft^3
CO_2	2.0% by volume
O_2	0.2% by volume
Nitrogen	3.0% by volume
Total inert gases	4.0% by volume
Hydrogen	400 ppm
CO	none
Halogens	none
Unsaturated HC	none
Water	7 lb/1,000,000 ft^3
HC dewpoint	45°F @ 400 psig
Heating value	975 Btu/ft^3 HHV minimum

These standards only cover delivery into a transport pipeline. The local distribution company can have a major impact on gas composition through local air and propane addition. The GRI funded a study of gas composition in 10 U.S. cities. The results, repeated here as Table 11, show wide variations in composition.

Some of the greatest anomalies in the study occurred because of the use of propane/air peakshaving. Propane/air peakshaving is used in some regions to provide fuel during peak demand times. Propane and air are mixed to a Btu content equivalent to the local natural gas. This gas is then injected, in mixtures as high as 50%, into the local pipeline gas. The use of propane/air is expensive for a utility. Thus, its use is minimized but is occasionally necessary during peak demand periods, especially along the Eastern Seaboard. A typical usage rate during peak demand periods is up to 20% of the overall volume; however, this number can rise as high as 50% during peak use. On a national level, propane addition accounted for only 0.03% of the total energy delivered through the national gas system (this does *not* include the propane normally contained in natural gas). A high-propane gas will have different combustion characteristics (ignition delay, flame speed, octane rating) than the Btu-equivalent "normal" gas, but the effect on engine operation was not discussed in the literature examined.

Table 11. National Weighted Data for 10 U.S. Cities, Propane - Air Peakshaving Considered [LT91]

Constituent/ Property	Mean	Standard Deviation	Minimum	Maximum	10th percentile	90th percentile
Methane %	93.2	5.5	55.8[9]	98.1	88.5	96.4
Ethane %	3.6	2.6	0.7	14.7	1.8	5.0
Propane	0.8	1.4	0.0	23.7[9]	0.3	1.3
C_4+ %	0.5	0.7	0.0	2.1	0.1	0.6
Inerts (CO_2, N_2) %	2.7	2.0	0.1	15.1[9]	1.0	4.7
Heating value, Btu/SCF	1,037		970	1208[9]	1023	1050
Specific gravity	0.603		0.566	0.883[9]	0.578	0.628
Wobbe number	1338		1198	1402	1312	1357
Mass A/F ratio	16.3		12.7*	17.1	15.7	16.8

LPG Composition

The composition of LPG depends on its source: whether it is extracted from natural gas or produced during the refining of petroleum. LPG is primarily propane, although it may contain significant amounts of ethane and butane as well. Data from the California Air Resources Board (CARB) indicate that the propane content of LPG delivered to CARB over a seven-year period (1982-1989) varied from ≈63% to 96% [Joh90]. Other sources place the range of propane in LPG from 50%-100% [KW83]. Further data from the CARB analysis indicated that the ethane content of the fuel was ≈15% in the early 1980s, but only ≈5% later in the late 1980s.

Commercially, there are four grades of LPG [RBW80]:

- Commercial propane, which is predominantly propane and/or propylene
- Commercial butane, which is predominantly butanes and/or butylenes
- Commercial butane-propane (B-P) mixtures, which are mixtures of butanes, butylenes, propane, and propylene
- HD-5 propane, which has not less than 90% liquid volume propane and not more than 5% liquid volume propylene.

[9] Values set by propane/air peakshaving gas composition.

According to Russell et al. [RBW80], only HD-5 propane is suitable as a fuel for spark ignition engines. However, analysis of LPG composition over time [Joh90] indicates that the 90% propane standard for HD-5 may only be met ≈50% of the time, and may occasionally drop substantially below (propane content ≈ 63%) the HD-5 standard. Certainly, more information is needed about the "quality" or composition of LPG at end-use fueling stations. Several oil companies (Conoco, Phillips) appear to be making efforts to produce standardized LPG fuels, which will probably be tightly regulated HD-5 type fuels.

In theory, LPG composition for automotive use is governed by American Society for Testing and Materials (ASTM) standard 1835. This standard specifies that the fuel must consist mainly of propane, with no more than 5% propylene and 2.5% of butanes or heavier HC. Other countries allow more butane in LPG, which ranges from a C_3/C_4 ratio of 90/10 in the United Kingdom, through 50/50 in other parts of Europe, to 20/80 in Italy [OC90]. Other restrictions are normally specified to limit:

- Residual matter to no more than 5% upon evaporation, to prevent clogging of regulators and metering systems

- Corrosion characteristics, to protect copper and brass fittings

- Water content, to prevent corrosion and line freezing.

The limitation on propylene is primarily due to its low knock resistance (low octane number), as shown in Table 12. Excess propylene concentration could lead to preignition and engine damage. Propylene is normally only found in LPG produced from oil refining. LPG extracted from natural gas does not normally contain propylene. A second concern with propylene is its photochemical reactivity, which is higher than that of propane. This could be an important issue in ozone non-attainment areas.

Table 12. Octane Rating of Propane and Propylene [Obe73]

	Research Octane No.	Motor Octane No.
Propane	112	97
Propylene	102	85

A final fuel composition issue with LPG is the presence of "black metallic residues." These were mentioned in verbal communications, but not in the written literature. The origin of these magnetic, metallic residues is unknown, although it is plausible that they could result from contact with rusty storage tanks or pipelines. It does not appear that these residues pose a problem in their normal concentrations.

Effect of Fuel Composition on Emissions

Southwest Research Institute has been active in exploring the effect of gas composition on engine performance and emissions [Kin91, LT91]. Scientists there have concluded that for a given equivalence ratio, the effect of fuel composition is minor. However, they also concluded that maintaining a fixed equivalence ratio is very challenging. As the fuel composition changes, the Wobbe index changes, resulting in a change in energy delivered to the engine. Their studies of fuel composition histories from a national gas composition survey indicate that composition-induced equivalence ratio variations of up to 12% are possible. This change in equivalence ratio can produce dramatic variations in lean-burn gas engine emissions: a variation of 6:1 in NO_x emissions, 9:1 in THC emissions, and 2:1 in CO emissions. Engines equipped with catalytic converters are known to be sensitive to the effects of gas composition (NO_x is particularly sensitive), although quantitative studies of stoichiometric engines were not unearthed in the study.

Performance

An often-cited complaint about natural gas vehicles converted from gasoline is the perceived loss of vehicle power. The loss of power is certainly real, and an estimate of the magnitude of the power loss can be obtained from basic stoichiometry:

Methane Stoichiometry: $CH_4 + 20_2 + 2(3.76)N_2 = 2H_20 + 2(3.76)N_2 + 1CO_2$

Propane Stoichiometry: $C_3H_8 + 50_2 + 5(3.76)N_2 = 3CO_2 + 4H_2O + 5(3.76)N_2$

Based on these equations, it can be shown that a stoichiometric methane/air mixture is 9.5% methane, and a stoichiometric propane/air mixture is 4% propane. Propane therefore displaces less air, allowing it the potential for higher power levels. In addition, at elevated pressure, the flame speed of propane is faster than that of methane, which also contributes to its greater power potential. Natural gas is often cited as producing a ≈10%+ power loss [Wea89], while the power loss on propane is often assumed negligible. This is reflected in calculations cited by Ford [MTM82b], which compare the engine displacement required for equivalent power on four fuels, shown in Table 13.

Table 13. Comparison of Range and Power of CNG and LPG with Baseline Fuels [MTM82b]

	Engine Displacement for Equal Performance	Range with 15-gal Tank (miles)
Gasoline	1.6	420
Diesel	2.0	600
LPG	1.6	345
CNG	1.8	120

Test Results

Test results indicate that the actual power loss often exceeds the theoretical values. A factor contributing to this additional power loss is related to fuel vaporization and manifold heating. The heat of vaporization of gasoline helps to cool the air/fuel mixture, producing the dense mixtures required for increased power.

Intake manifolds on carbureted and throttle body injected engines are often heated to help minimize the amount of gasoline that collects on the floor and walls of the manifold. If an engine with manifold heating is converted to a gaseous fuel, the hot manifold will heat the intake mixture and reduce the power level beyond the figures mentioned previously. Dedicated vehicles and fuel injected vehicles seldom have manifold heating, and thus exhibit improved power.

Power tests were conducted by General Motors Corporation using two 5.7-L engines with standard gaseous carburetion equipment [Gen72]. A comparison of the results obtained showed that the engine produces 8% less power with LPG than with gasoline, and 14.6% less power with natural gas. The study also reports that CNG requires a 5° greater spark advance, and that the ignition advance for LPG is approximately the same as gasoline.

B. C. Research tested seven conversion kits (all were mechanical kits: Beam, Mogas, Diversified Fuel Systems, Dual Fuel Systems, CNG Fuel Systems, Ltd., OMC Lincoln, and ECO Systems, Inc.) by installing them on three different vehicles. The power tests showed that on all three vehicles a 20% power loss resulted from the conversion [AGP85].

Power tests with a new generation of electronically controlled gaseous fuel injection (Stewart & Stevenson Gaseous Fuel Injection [GFI] System) revealed the power losses shown in Table 14 [Law91] relative to gasoline.

Table 14. Power Characteristics of Electronically Injected Natural Gas Vehicles [Law91]

Engine & Vehicle	BHP	RPM	Percentage change from gasoline
3.1-L multiport injected (MPI) V-6 Lumina	98	4500	-10.9%
4.3-L throttle-body injected (TBI) V-6 S-10	118	4200	-13.2%
5.7-L V-8 G-Van	120	3800	-14.3%
6.0-L TBI V-8 School Bus	124	3600	-18.4%

Extensive testing by a utility fleet reveal an aggregate power loss of ≈15%. An interesting note is that some operators report an *increase* in perceived power [NAF90, Gre89] on CNG. A survey of 731 natural-gas-vehicle (NGV) owners in Canada revealed that the owners were split on the issue: as many owners believed their vehicles performed better on CNG than on gasoline as believed that gasoline gave the best performance [Gre89]. Conversations with LPG vehicle owners reveal similar perceptions, although the information is anecdotal.

The results of extensive testing of NGVs by Mountain Fuels Co. is presented in Table 15. The figures indicate an average power loss of 9.2%, which is very close to the 9.5% theoretical value.

Table 15. Comparison of Vehicle Power on Gasoline and CNG

Vehicle	Engine Displacement	Maximum Power Gasoline	Maximum Power CNG
1989 Chevrolet pickup	350 in^3 V-8	98	95
1990 Ford Taurus	3.0-L V-6	68	60
1989 Ford pickup	2.3-L 4-cyl	78	62
1989 Chevrolet 1-ton truck	454 in^3V-8	110	100
1990 Chevrolet pickup	305 in^3 V-8	104	92
1989 Ford Tempo	2.3-L 4-cyl	58	50
1985 Mercury Grand Marquis	302 in^3 V-8	72	62
1989 Dodge Mini Van	4-cyl turbo	95	92
1990 Dodge pickup	360 in^3 V-8	94	87
1991 Chevrolet pickup	305 in^3 V-8	100	94
1991 Chevrolet Blazer	350 in^3 V-8	104	96
1990 Dodger Ramcharger	360 in^3 V-8	97	85
1989 Chevrolet Celebrity	2.8-L V-6	62	58
1990 Chevrolet pickup	350 in^3 V-8	95	90
1989 Ford Airport Shuttle	460 in^3 V-8	110	95
1990 Dodge 1-ton van	360 in^3 V-8	100	89
1990 Ford Taurus	3.8-L V-6	80	72
1990 Chevrolet pickup	350 in^3 V-8	108	95
GMC 1 ton pickup	350 in^3 V-8	90	90

Average Power Loss: $$\frac{Power_{Gasoline} - Power_{CNG}}{Power_{Gasoline}} = 9.2\%$$

Diesel engines are normally "smoke limited" when operating on diesel fuel. When operating on fumigated natural gas, loss of power does not appear to be an issue, if the controls are well integrated. The challenge is to prevent peak cylinder pressures from rising above acceptable levels [GPB87].

Drivability

Driver satisfaction is a function of the crispness of vehicle response as well as raw power. Fleet operators do occasionally report sluggish response from CNG and LPG [Gas91] vehicles. In general, however, I believe that these complaints result from the sluggish response of the mechanical control systems, and not from the actual power loss due to the fuel. Obviously, if a vehicle is at full throttle, it is operating in a power-limited mode, but this typically represents only a very small percentage of driving time.

Drivability can have an indirect impact on emissions. The EPA notes that CNG can result in a deterioration of drivability [EPA88]. Fleet operators may therefore richen the fuel mixture to improve drivability, increasing emissions in the process. Although the EPA does not currently regulate conversions, it has indicated that it may require safeguards against operator adjustment. The EPA does not address LPG in this study. Karim [KW83] reports smoother engine idling on gaseous fuels. He also reports that both spark-ignited and diesel engines are quieter when operating on gaseous fuels.

Diagnostics

Difficulties can arise from the interaction of the fuel delivery system with the OEM engine control computer. In order to maintain optimal performance, computer-controlled engines watch for unexpected conditions. If these conditions are encountered, the controller may set a fault code. In some circumstances, it may actually alter the engine operation, resulting in degradation of power, efficiency, and emissions. An alternative fuel equipment certification from the State of California will require that the system *not* affect vehicle diagnostics after 1993.

Knock Sensor

At certain intervals, the engine may attempt to create light knock to verify the function of the knock sensor. On high octane fuels such as CNG or LPG, it may not be possible to cause knock. The electronic control module (ECM) may therefore assume that the knock sensor is malfunctioning and set a sensor failure code. On some vehicles, the ECM will retard ignition timing by up to 10°, which can have negative effects on power and fuel economy.

EGR

The ECM can test the EGR system by activating EGR and monitoring the response of the oxygen sensor. On some non-feedback dual-fuel conversions an "oxygen fix" is installed to prevent "mislearning" of the adaptive gasoline tables. The fix can cause the diagnostic system to assume an EGR failure and set a sensor failure code.

Lean Acceleration Error

During hard acceleration, a gasoline-fuel injection system will richen the mixture for power. CNG and LPG systems generally remain stoichiometric. If the ECM expects a rich signal and sees a stoichiometric response, an O_2 sensor code may be activated.

Rich Deceleration Error

This is the opposite of the previous condition. During hard deceleration, the gasoline fuel injection system will shut off fuel completely. The ECM therefore expects a lean response during hard deceleration. If this does not occur, an diagnostic code may be triggered.

Fixes

In order to alleviate the negative consequences of certain error codes, hardware "fixes" have been developed.

Add-on "Fix"

An aftermarket device termed a "fix" can be used to circumvent problems with mislearning or false diagnostics. These "fixes" generally tie in to sensor lines and feed false (but expected) signals to the ECM during operation on the alternative fuel. These devices can cost up to $100, and may technically be considered to be "tampering," although no legal issues have been raised to date.

Prom Disabling

An inexpensive and permanent solution to problems with diagnostics is to disable them within the ECM. It is generally possible to change a flag within the ECM Programmable Read Only Memory (PROM), which will disable the diagnostic function. The problem with this solution is that the diagnostics are valuable when operating on gasoline, and disabling them could void vehicle warranties.

Desired Solution - the Alternate Fuels Acceptance Port

A long-term solution might be to equip vehicles with an Alternate Fuels Acceptance Port (AFAP), which would cause the engine ECM to switch to a mode compatible to the fuel in use [Car91]. The port could also be used to send information on the amount of remaining fuel to the fuel gauge.

Conversion Kits - Gasoline Engines

Nature of the Problem

A study of "first-generation" propane conversion equipment conducted at the University of Toronto [Wal89] concludes:

- First-generation propane carburetion systems do not consistently provide optimum A/F ratios to an engine throughout its load and speed range.

- Optimum spark timing for propane cannot be readily predicted from the spark timing for the gasoline version of the same engine. This factor makes the installer's task nearly impossible and seriously compromises propane conversions, which must compete against factory-calibrated electronic systems for gasoline.

The shortcomings of first-generation CNG equipment are confirmed by Weaver [Wea89], Klimstra [Kli87], and others. A case study of a fleet conversion to LPG illustrates the potential magnitude of the problem of poor installations. Leggs Products, Inc. in Winston-Salem, N.C. converted 600 half-ton Ford vans and step vans to LPG [NAF90]. The results were "disastrous," in the words of the fleet manager. The primary problem was poor quality installation of the conversion equipment. Two of the vehicles reportedly caught fire as they were being driven home from the conversion company. A third caught fire while parked at an employee's home. The fleet manager also reported difficulties in getting the vehicle manufacturer or converter to honor warranties. Finally, all the vehicles were converted *back* to gasoline operation, at great expense.

In a more methodical test, seven CNG conversion kits (Beam, Mogas, Diversified Fuel Systems, Dual Fuel Systems, CNG Fuel Systems Ltd., OMC Lincoln, and ECO Systems Ltd.) were evaluated by B.C. Research. Reporting of the tests does not indicate whether any of these systems used oxygen feedback.

Each of these systems was evaluated on the following three vehicles:

- Dodge 600 ES - 2.2-L 4 cylinder engine with 5-speed manual transmission
- Chevrolet S-10 truck - 2.8-L V6 engine with 5-speed manual transmission
- Ford F250 pickup truck - 5.0-L V8 engine with 4-speed manual transmission.

The results of the test showed that the power loss of natural gas was approximately 20%, double the theoretical 9.5% loss. Accuracy of fuel metering was ±10% of the stoichiometric setpoint, an excessively wide range. Emissions were not measured in this study.

Equipment Suppliers

A list of suppliers believed to be *actively* engaged in manufacturing CNG and LPG equipment is given in Table 16. The AGA publishes a directory of vendors involved in the CNG industry. This list includes 47 vendors under the category "Conversion and Carburetion." Many of these vendors are only installers, and some manufacturers of equipment are not included. Table 16 contains a subset of vendors included in the AGA list, as well as other vendors known to be active in CNG and LPG activities.

Table 16. Companies Known to Manufacture CNG and LPG Conversion Kits [composite]

Company	Location	Product
AG Holland	Holland	LPG and CNG conversion kits
Algas	Dallas, TX	LPG kits, primarily specialty equip. (forklifts, etc.)
Alles Corp.	Downsview, Ontario	Gas flow control computer
*Automotive Natural Gas, Inc. (ANGI)	Milton, WI	CNG conversion kits
BKM/Servojet	San Diego, CA	Computerized CNG conversion kits for gasoline and diesel engines
Carburetion Lab	Miami, FL	CNG conversion kits for diesels
*Century Alternate Fuels	Pensacola, FL	CNG & LPG conversion kits
*Clean Fuels	Martinsburg, WV	CNG conversion kits
Combustion Labs	Riverdale, GA	CNG conversions for diesels
Deltec Fuel Systems	The Netherlands	CNG & LPG conversion kits
ECO Fuel Systems, Inc.	Langley, British Columbia	CNG conversion kits
Electromotive, Inc.	Chantilly, VA	Computerized CNG conversion kit based on universal gasoline control computer
ETRA S.r.l.	Italy	CNG conversions for gasoline & diesel engines
Garretson Equipment Co., Inc.	Mt. Pleasant, IA	CNG & LPG conversion kits
*IMPCO	Cerritos, CA	CNG & LPG conversion for
Industrial GasTruck	Waukonda, IL	LPG conversion equipment
Vialle	Holland	LPG conversion kits

Table 16. Companies Known to Manufacture CNG and LPG Conversion Kits [composite]

Company	Location	Product
J & S Carburetion, Inc.	Dallas, TX	LPG conversion equipment
Landi Renzo S.p.A.	Italy	CNG & LPG (LPG appears inactive) conversion kits, including diesel
Mark II Innovations	Windsor, Ontario	CNG conversion kits
*Mogas	Burnaby, British Columbia	CNG conversions, including diesels
NCF Caithness	Long Beach, CA	Prototype computerized CNG conversion system
OHG	Santa Fe Springs, CA	CNG & LPG kits
ProMatic Corp.	Elkhart, IN	CNG conversion kits
Rodagas Energy Systems, Inc.	Roseville, MI	CNG conversion kits
Stewart & Stevenson	Denver, CO	CNG & LPG conversion kits for gasoline & diesel engines
Tecogen	Waltham, MA	Custom-engineered CNG conversion equipment
Thermal Efficiency, Inc.	Seattle, WA	"Throttle-body" CNG conversion kits
TNO Road-Vehicle Research Institute	Holland	CNG and LPG conversion equipment - largely R&D
Transport Fuel Systems	New Zealand	CNG conversion kits for automotive and diesel engines
Tri-Fuels Inc	Baton Rouge, LA	CNG conversion kits
YugoTech	Canada	CNG conversion kits

*Indicates firms that currently have or are poised for major market presence.

Metering Systems - General

Fuel metering systems can be classified according to their degree of sophistication and (presumably) their metering accuracy. The basic categories include:

- Non-feedback mechanical metering
- Mechanical metering with electromechanical O_2 feedback
- Mechanical feedback with O_2 feedback and adaptive memory
- Fully electronic systems.

Metering Systems - Mechanical

The vast majority of gas-fuel control systems in use are mechanical in nature. Although there are many different strategies, most of them use one of the following techniques:

Venturi

A typical venturi system utilizes a series of gas pressure regulators to reduce the fuel to atmospheric pressure. A venturi installed in the intake air duct is used to "draw" fuel into the engine in proportion to the mass flow rate of air into the engine. Venturi systems are marketed by ANGI for CNG.

Mechanical Mass Flow Rate

This system is utilized in the IMPCO fuel delivery systems for LPG and CNG. The pressure change across a diaphragm causes a gas valve to open, metering fuel into the engine.

Variable Area

The variable area system meters fuel gas through a small throttle body that is geometrically similar to the engine air throttle. If the air and fuel supply pressures are the same, and the two throttle plates (air and gas throttle plates) are set at the same angular positions, the A/F ratio will be determined by the relative bore area of the air and fuel throttle assemblies. The advantages of the variable area system include rapid response and minimal air restriction. This concept is used in the Century line of CNG and LPG equipment produced by PACER Industries in Florida.

Metering Systems - Mechanical with Feedback

The mechanical systems as described above cannot compensate for equipment variation or for variations in fuel composition. Some of the mechanical systems can be retrofitted with limited feedback compensation capabilities. These systems use an exhaust gas oxygen sensor to provide a correction signal to provide a rich or lean bias to the fuel controller. These hybrid systems can provide excellent steady-state fuel control, although the transient response is still dependent on the quality of the mechanical calibration. IMPCO manufactures a mechanical system with feedback.

Metering Systems - Mechanical with Feedback and Adaptive Memory

This is a relatively new development, and consists of a mechanical metering system with electromechanical O_2 feedback. A companion controller has reportedly been developed that will monitor engine speed and manifold pressure and store the amount of air to fuel ratio required at each "cell." This will provide closer metering accuracy during transients than a simple mechanical/feedback system. This system is offered by IMPCO.

Metering Systems - Computer-controlled

Several companies are now developing computer-controlled fuel delivery systems for gaseous fuels. These systems provide the *potential* for accurate, adjustment-free operation, although none of the systems has completed long-term, widespread testing.

Stewart & Stevenson GFI

The Gaseous Fuel Injection (GFI) System is a microprocessor-controlled fuel delivery system that was originally developed by ORTECH International and is now being marketed by Stewart & Stevenson Power, Inc. The GFI uses parallel coarse and fine metering strategies. The coarse metering is provided by a bank of five solenoid valves of varying flow rates. The solenoids can be combined into 32 discrete combinations to provide 32 different flow rates. Fine control is provided by two additional pulsewidth modulated injectors. By using this two-stage strategy, accurate system response is obtained in less than

5 milliseconds. The GFI system monitors engine speed, manifold absolute pressure, barometric pressure, fuel pressure, intake air temperature, fuel temperature, manifold temperature and exhaust gas oxygen. These sensors are used in a speed/density strategy to determine the air flow rate and the desired fuel flow rate. The GFI is being marketed as a "universal system" that can be installed on almost any vehicle. Currently, the GFI is only available for natural gas, although the system is being adapted for use with LPG.

IMPCO/Air Sensors

The Air Fuel Electronic (AFE) system developed by IMPCO and Air Sensors taps into existing engine sensors to determine air flow rate. Fuel is controlled by a high speed fuel throttle, with a special mass sensor to provide feedback and ensure accurate fuel delivery. A special "T" connection is designed for each engine family, and plugs in between the engine computer and wiring harness. This connector should speed up system installation, although it may also mean that only the more popular engine families will be supported. The IMPCO system is eventually expected to support both CNG and LPG.

BKM/Servojet

BKM has developed an engine controller that drives a set of its Servojet gas injector valves. The controller is quite sophisticated, and includes the capability to operate sequential, multiport gas injection. Recently, the company announced plans for widespread distribution of the system designed primarily for natural gas.

SwRI/DAI

SwRI has designed a fuel controller that uses a high-speed proportional control valve manufactured by Bendix. Although SwRI initially designed the system for internal use, the institute has undertaken a joint effort with DAI to design a commercial product for natural gas application. The basis of their control module is the engine's Electronic Control Unit (ECU). Outputs from the ECU are routed through a "Translator Box," which compensates for fuel pressure and temperature. The output of the Translator is a signal that is compatible with the Bendix valve.

Electromotive

This system is an adaptation of Electromotive's speed/density gasoline-fuel delivery system. In the Electromotive system, a computer is used to establish a setpoint fuel delivery pressure based on engine power. Based on these setpoint pressures, a pair of solenoids is used to meter high-pressure fuel into or out of a pressure dome on a pressure regulator. Thus, the system relies on a servo controlled pressure regulator which is controlled by software adapted from Electromotive's gasoline delivery system. Electromotive ties into existing engine sensors and uses a proximity sensor and toothed wheel for speed sensing. It does not appear that the Electromotive system is sufficiently well developed for widespread use.

Evaluating the Performance of a Fuel Delivery System

Obviously, FTP emissions testing is the test of choice for evaluating overall vehicle emissions. However, items such as catalyst type, vehicle age, and vehicle weight can obscure the results. A valuable technique for assessing the accuracy and responsiveness of a fuel delivery system is the A/F histogram (see Figure 1). The histogram is constructed by measuring the amount of time spent at different A/F ratios during a test. The ideal response for a stoichiometric engine would be a narrow spike at an equivalence ratio of 1.0. As transient response worsens, the histogram will flatten out, reflecting a greater amount of time at non-optimal conditions. Obviously, this test is meaningless without close cylinder-to-cylinder distribution.

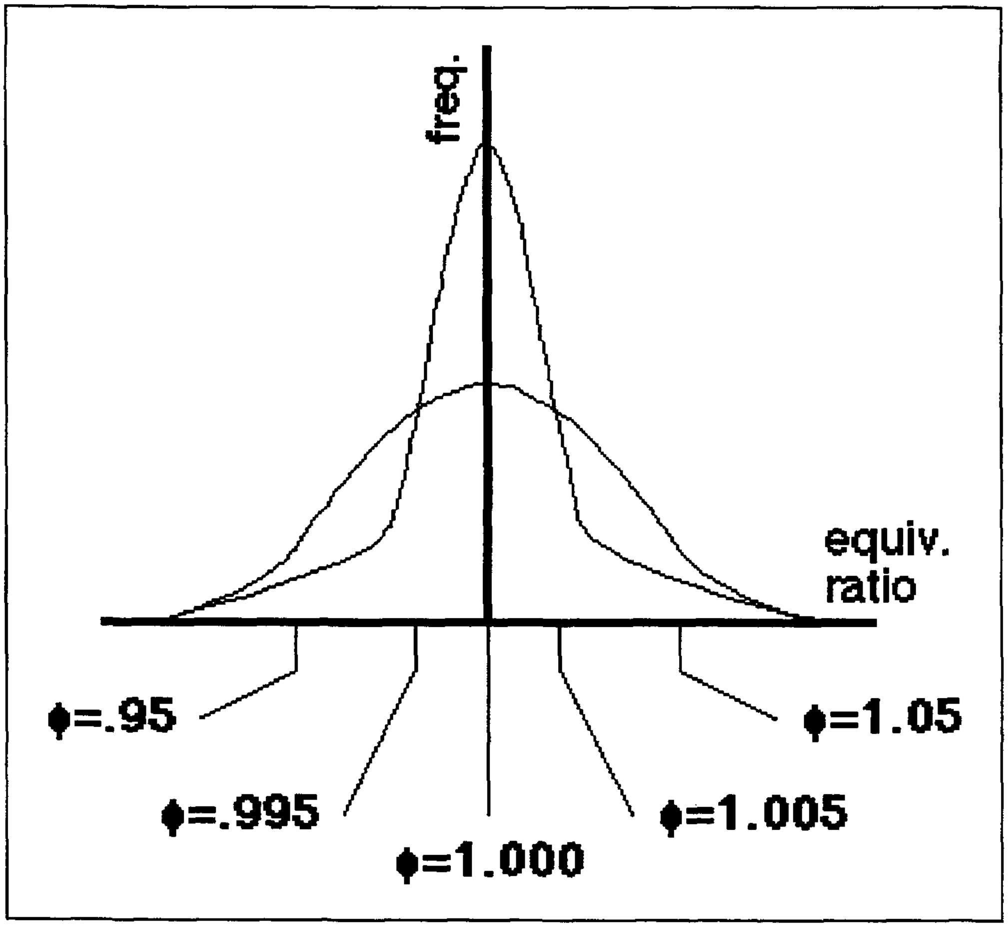

Figure 1. Air/Fuel Histogram

Conversion Equipment - Diesel Engines

Conversions of diesel engines are much more involved than conversion of spark-ignited engines. The autoignition temperature for CNG or LPG is much higher than for diesel fuel, so higher compression pressures and temperatures are required. This results in higher peak temperatures in the cylinder, resulting in higher NO_x production [Kli90]. Therefore, it is common to use spark ignition, a glow plug, or pilot injection with diesel fuel to ensure ignition at lower temperatures. Many engines have been built and/or modified to run with spark assist or with prechamber ignition. However, all of these systems require major engine modification. The option most commonly adopted for aftermarket conversion uses fumigation of natural gas, with ignition provided by a small diesel pilot. These are commonly referred to as dual-fuel engines.

Dual-fuel engines use a combination of gaseous and diesel fuels. The strategy is to displace as much of the diesel fuel as possible, to reduce fuel cost and particulate emissions. A diesel pilot or alternative ignition enhancement is required. For diesel pilot systems, it is widely reported that a variable schedule of pilot fuel is desired [GPB87], suggesting the desirability of computer control. Dual-fuel systems are available that do not utilize a computer-controlled pilot [CLI91c], although performance of this type of system has been shown is expected to be less than optimal [FE91].

Gaseous fuel delivery systems for diesel engines can be classified as fumigated or injected systems. Fumigated systems are popular because of their simplicity, as the gaseous fuel is typically introduced to the engine upstream of the intake manifold. Fumigated systems often employ a mechanical carburetor for fuel metering. A serious drawback to the use of fumigated systems are the potentially high levels of HC emissions. This results from the escape of fuel during the scavenging process in two-stroke cycle engines (if unthrottled) or during the valve overlap period in four-stroke cycle engines. This problem can be alleviated through the use of timed gas injection. An effective injection system will inject gas late in the scavenging or intake cycle, ensuring that no fuel passes directly through the exhaust. This will also produce a stratified charge for stable light-load combustion in two-stroke cycle engines. It is possible to inject high-pressure fuel gas directly into the cylinder during the compression or power strokes. The high-pressure strategy is being pursued at the OEM level, although the mechanical complexity makes this an unlikely strategy for retrofit applications.

A second source of high HC emissions in two-stroke cycle engines results from the incomplete combustion that occurs at high air/fuel ratios. High air/fuel ratios occur at light loads, with the result that many dual-fuel engine control schemes eliminate the use of the gaseous fuel at light loads. Air throttling can be used on two-stroke cycle engines to ensure a constant air/fuel ratio and to reduce the scavenging losses that would be produced in an unthrottled engine. Unfortunately, this can result in air and oil leakage past valve guides and piston rings in an engine that was not designed for operation with negative manifold pressure.

In-use Test Results

Very few in-use data on medium- and heavy-duty vehicles are available. A recent test conducted in Texas supports the concern with fumigated systems and the need for further in-use testing. A test of four heavy-duty dump trucks was conducted by SwRI for the city of Houston [FE91]. This included the testing of two Ford F700 7.4-L gasoline-powered trucks and two GMC 8.2-L diesel-powered trucks. Each of these trucks was first tested on the base fuel. The gasoline trucks were then converted to CNG, and the diesel trucks to dual fuel (CNG with a diesel pilot). Conclusions reported by SwRI included:

- NO_x was 50% higher with CNG than gasoline.
- NMHC and CO were 20%-30% lower with CNG than gasoline.
- Transient cycle fuel economy was 5% higher on CNG than gasoline. Idle fuel consumption was 25% worse on CNG than gasoline.
- Total HC emissions were *30 to 50 times higher* with dual fuel than on baseline diesel. NMHC levels were 5 to 7 times higher with dual fuel than on baseline diesel.
- NO_x was 50% lower with dual fuel than on baseline diesel.
- Particulates were 50% lower with dual fuel than on baseline diesel.
- Fuel economy was 25% lower with dual fuel than baseline diesel.

Metering Systems for Heavy-duty Vehicles

The following gaseous-fueled systems are available for retrofit installation on diesel engines.

B.C. Research/Natural Energy Research Ltd.

B.C. Research and Natural Energy Research [GPB87] have developed a microprocessor-based fuel control system that allows variation of pilot fuel as a function of engine speed and load. Engine mapping was performed with the intention of maintaining comparable cylinder pressure characteristics. Pilot fuel for the system varies from 35%-75%. The system utilizes a Motorola 68705 microprocessor for the controller. Diesel injection is controlled by a stepper-motor-controlled fuel injection pump, and natural gas is metered with a specially designed cone-in-orifice metering valve. No commercialization plans have been reported, but the system appears suitable for development into a conversion unit. Maps have been developed for a turbocharged John Deere 6466T engine (165 hp) and a naturally aspirated Caterpillar 3208 engine (210 hp). No emissions results were reported, although engine torque and efficiency are similar to stock diesel operation.

Woodward Governor

Woodward Governor has developed a controller for the Cummins L10 engine. The governor maintains the engine speed between 600 and 2200 rpm regardless of load by varying an electronically controlled throttle. Fuel metering is provided by a mechanical carburetor. The system communicates with the electronically controlled transmission and also controls ancillary features such as door interlock and fast idle when the air conditioner is in use. The natural gas L-10 is a spark-ignited engine, extensively modified from the diesel version. As such, it does not fall under the simple retrofit category, although it is included here as a possible rebuild option (similar to the Stewart & Stevenson 6V92).

BKM/Servojet

BKM has developed a compact, low-cost, gaseous-fueled injector [BJP91, Bec90, BKM91]. The company has also adapted a sophisticated control computer, originally developed for control of diesel engines, to use with natural gas. The gas-fuel control system consists of a battery of fuel injectors arranged for sequential port fuel injection, with control provided by their "Eagle" controller. In theory, the control system is universally adaptable to any spark-ignited engine. It is also proposed that the controller could be used with "micropilot" oil injection in diesel applications. There is a possibility that the system may be produced in larger numbers for distribution to established conversion companies.

Alternative Fuel Systems

Alternative Fuel Systems, Inc., and Access Technology, Inc., operate a joint venture to manufacture and market a microprocessor-controlled natural gas/diesel system [CFR91c]. The system is based on computer-controlled gas fumigation, delivered through separate gas injectors for each cylinder. The injectors are BKM/Servojet injectors. The system has been applied to the following engines: Mercedes Benz Models OM352 and OM 366, Belarus D-144, RABA 2356, Cummins GCT8.3[10] and NT855, and Hyundai D6BR.

[10] It is not clear that Cummins actually produces a G (gas) version of this engine.

Stewart & Stevenson TPI

Stewart & Stevenson Power, Inc. (with assistance from ORTECH, DAI, and Lucas) has developed a high-speed natural gas injector valve that is used in a conversion kit for the Detroit Diesel 6V92 engine [WSA90]. This system is referred to as timed port injection (TPI), and uses an injector mounted low on each cylinder of this turbocharged, two-stroke engine. Natural gas injection into each cylinder begins late in the scavenging process and concludes early in the compression process. Ignition is via diesel pilot. Electronic control of gas injection and the diesel pilot are provided via a modified DDEC: Detroit Diesel Engine Control (DDEC) system, with specialized driver electronics required to operate the gas injectors. The TPI system claims to provide efficiency benefits over a fumigation system. The system has demonstrated a maximum efficiency of 35% versus 40% for pure diesel operation and 27% for fumigated gas operation.

Carburetion Labs

Carburetion Labs (Miami, Florida) produces a mechanical fumigation system that fumigates natural gas through their KG-5000D Diesel Mixer in a ratio of 80% natural gas and 20% diesel. The information received does not allow any further technical discussion [CLI91c]. Several of these systems have been installed in school buses in Texas.

Certification

A major issue influencing the performance of gaseous fueled vehicles is the quality of workmanship in the conversion itself. This situation should change as production CNG and LPG vehicles become available directly from automakers. For the next few years, however, it is expected that even production vehicles will be "upfits," or factory-installed conversions. In the United States, GM, Ford, and Chrysler are all developing CNG vehicles for near-term introduction. The LPG situation is mixed. GM has recently added propane conversion options to some of its medium-duty truck choices: the GMC Topkick and the Chevrolet Kodiak vehicles with 6-L or 7-L engines. At the same time, Ford Motor Company has dropped its long-time propane conversion option on its medium-duty F-600, F-700, and F-800 trucks [CFR91c].

Currently, only Colorado and California are believed to have certification programs for CNG/LPG conversion kits. In Colorado, Regulation No. 14 [CO90] requires that dual-fuel vehicles be tested on gasoline and on the alternative fuel, and that emissions levels on gasoline do not degrade from the conversion. The alternative fuel must produce emissions lower than the original certification standard, or lower than the vehicle before conversion. The certification agency (Mobile Sources Division of the CDH) reserves the right to cancel a certification if random field testing reveals that in-use vehicles have significantly higher emissions than the certification results. In-use surveillance has identified vehicles with high in-use emissions. One example cited in [CDH90] was a 1988 Lincoln that produced 15 g/mi of CO. After readjustment, the vehicle emissions dropped to 2 g/mi CO. The CDH is currently conducting a study of in-use vehicle emissions, which is expected to be released in mid-1992.

According to the California Air Resources Board, "properly installed LPG and CNG conversion systems have shown excellent performance in use. However, improperly converted vehicles have been found to produce excess emissions" [CARB91]. The California certification procedure is similar to the Colorado procedure, but with several important new requirements:

- Drivability must not be degraded. It is not clear, however, what standard will be used to evaluate drivability.

- On-board diagnostics must not be impaired. This could have impact on "fixes" discussed previously.

- System must not be manually adjustable: "With the exception of idle speed control and throttle position control, no component or calibration of the fuel system that could affect emission performance shall be adjustable by the system installer or the vehicle's user" [CARB91].

Engine Life/Engine Wear

Natural gas and LPG are generally considered to reduce engine maintenance and wear in spark-ignited engines. The most commonly cited benefits are extended oil change intervals, increased spark plug life, and extended engine life. Conclusive studies of the effect of gaseous fuels on engine life were not identified in the literature. However, two items appear to be responsible for increased life. Natural gas and LPG both exhibit reduced soot formation over gasoline. Reduced soot concentration in the engine oil is believed to reduce abrasiveness and chemical degradation of the oil. A related effect that has been important until recent years pertains to lead oxides. These oxides occur because of the use of leaded gasoline and can be very abrasive. As leaded gasoline continues to be phased out, the importance of this effect will diminish. A very significant effect is believed to occur during cold starting. Gasoline-fueled engines (particularly carbureted vehicles) require very rich operation during cold-starting and warmup. Some of the excess fuel collects on the cylinder walls, "washing" lubricating oil off walls and contributing to accelerated wear during engine warmup [Dur89]. Gaseous fuels do not interfere with cylinder lubrication.

The soot level in diesel engines is much higher than in gasoline engines. Therefore, the longevity impact from gaseous-fuel operation is potentially greater with diesel engines than with gasoline engines. However, there is also a potential that poorly designed diesel retrofits can result in excessive cylinder pressures, which could shorten engine life.

Converted Spark-ignited Engines

Reliable information on the life of converted engines is sparse. One interesting study did examine the life of an automotive engine converted for use in a stationary cogeneration application. In a derated 454-in^3 automotive engine operating on natural gas, a life of 20,000+ hours has been demonstrated when operated continuously at 86 hp at 1820 rpm[11]. Modifications included heavy duty pistons, moly-plated piston rings, double roller-chain camshaft drive, and a high capacity oil pump. The engine used special valve seats to increase seat life and softer valve springs to reduce valvetrain loading friction. This engine was used in a cogeneration application with an overall efficiency of electrical generation of 26.4%, and cogeneration heat recovery of 57%, based on the higher heating value of the fuel [Kop84].

Valve face and valve seat wear is often mentioned as an issue with gaseous fuels. This is more of an issue for engines designed for operation on leaded gasoline, as these engines rely on the lead for valve seat lubrication. Heavy-duty engines and engines designed for operation on unleaded gasoline typically have hardened valves and seats, making them more suitable for use with gaseous fuels. At one point in the early 1980s, both Ford and Chevrolet produced "conversion ready" vehicles for LPG service. The modifications were believed to include the installation of hardened valve seats and removal of valve rotators. Hardened valve seats are generally recommended for gas-fueled engines, which were originally

[11] Although, as soon as one reviewer notes, 86 *hp*/454 in^3 = 0.189 *hp*/in^3: an engine should run a long time at this loading level on *any* fuel.

built for use with leaded gasoline [KW83]. Hardened valve seats were required to provide the 20,000+ hour life on the 454 cubic inch displacement (CID) cogeneration engine. Valve life is a major concern on turbocharged heavy-duty engines. Research is under way to develop valves with 10,000-hour life for these heavy-duty engines.

Natural gas and LPG are well suited to lean-burn operation. However, the increased oxygen content creates an oxidizing environment, which could potentially have detrimental effects in engines that are not designed for lean operation. One author states that if a hot spot forms in the engine, "the oxygen will react with the hot metal, causing guttering of the component" [Mil88b], although this has not been confirmed by testing. This hot, oxidizing environment may also be expected to reduce spark plug life in lean-burn engines operating at high IMEP. It should be noted that these comments were made with respect to a stationary, natural gas engine, for which 10,000+ hours of operation at high power levels are desired. Spark plug life is proving to be a problem with turbocharged lean-burn engines.

Converted Diesel Engines

Theoretically, a diesel engine experiences a constant pressure combustion process, while a spark-ignited engine undergoes constant volume combustion. Thus, for a converted engine to produce the same *average* cylinder pressure (i.e., power) on a gaseous fuel as on diesel fuel, the peak cylinder pressures are expected to rise. This may have a detrimental effect on the life of engine bearings. However, because spark-ignited engines use lower compression ratios, the peak pressures are lower. One study has confirmed that diesel engines converted to dual-fuel operation experience higher peak cylinder pressures than when operating on diesel alone [AGP85].[12] The magnitude of this increase may be as much as 35% on a poorly implemented conversion. This is the result of rapid combustion of the fumigated air/natural gas mixture. High-pressure gas injection could alleviate this problem, but direct in-cylinder gas injection is still in the development stage.

Safety

The physical properties of CNG, LPG, unleaded gasoline, and diesel fuel are reported in Table 17. The data indicate that CNG and LPG are less likely to autoignite on hot surfaces than gasoline or diesel, and require higher energy for ignition. In the case of a fuel spill, gasoline, diesel fuel and LPG are heavier than air and will collect and burn at ground level. Natural gas is lighter than air; in the case of a vehicle fire, buoyancy effects dictate that the fuel will burn above ground level, where it is less harmful to vehicle occupants. Liquefied natural gas (LNG) has some special safety considerations, but is not within the scope of this study.

[12] There is some counter evidence to indicate that the peak cylinder pressures and rate of pressure rise may be *lower* on natural gas engines.

Table 17. Comparative Combustion Properties of Fuels [Mur90, KW83]

	CNG	LPG	Unleaded gasoline	Diesel fuel
Autoignition temp. °C	540	450	220	225
Spark ign. energy, mJ	0.29	0.25	0.24	0.24
Flammability limits, vol %	5 - 15	2.1 - 9.5	1.4 - 7.6	0.6 - 5.5
Detonation limits, vol %	6.3 - 13.5	3.4-35		
Stoichiometric air/fuel	17.2	15.7	14.7	15.0
Cetane number	-10	-5 - 0	8 -14	40 - 47
Flame visibility, relative	0.6	0.6	1.0	1.0
Flame spread rate, m/s	N.A. (gas)	N.A. (gas)	4 - 6	0.02 - 0.08
Peak flame temperature, °C	1790	1990	1977	2054
Odorant	Detectable @ 1/5 lower flammability limit	Detectable @ 1/5 lower flammability limit	N.A.	N.A.

Safety Studies

A study by Klausmeier at Radian [Kla89] analyzed safety risks associated with alternative fuels and concluded that the lowest safety risk is associated with diesel fuel, and the highest with gasoline. Dedicated CNG was judged safer than gasoline, methanol, and LPG, although it is not clear what the rating for dual-fuel CNG/gasoline would be. LPG was judged roughly equal in safety to gasoline. The study noted that tank failures in CNG and LPG vehicles are rare, with most fires caused by leaky connections. This study repeats a comment that explosions of LPG tanks have been reported during crash tests, with intense shooting flames resulting.

The Los Alamos National Laboratory conducted a study of the safety of gaseous-fueled vehicles, using an interactive group method to elicit expert judgment from a group of experts [KPL83]. In this study, CNG, LNG, LPG, gasoline, and diesel fuel were examined under different accident scenarios. The following selected conclusions were reached:

- Statistical analysis of the safety of gaseous-fueled vehicles will be questionable because of the small number of vehicles in use in the United States. A bias may also exist because of the high proportion of fleet operation of CNG and LPG vehicles. Fleet maintenance and safety standards are generally more demanding than those for the general public. Statistical information from other countries with larger fleets is generally of low quality. In addition, foreign biases would be incurred to varying automotive and equipment standards.

- The safety records of CNG and LPG appear to be very good.

- Diesel fuel is significantly safer than the other fuels.

- Gaseous fuels have a significant explosion hazard relative to gasoline in the enclosed residential garage, but pose a lesser physiological hazard. All fuels appear safe in a well-ventilated public garage.

- For fueling line ruptures, the pressurized gaseous fuels (LPG and CNG) exhibit higher hazard levels, although present technology can reduce this to acceptable levels. No safety differentiation was made between LPG, and CNG.

- Under the collision scenarios examined, diesel fuel was ranked as the safest fuel, followed in order of decreasing safety by CNG, LPG, and gasoline. LPG appears to have a lower safety ranking than CNG because of the wider relative flammability range of LPG and a higher perceived explosion hazard.

The Los Alamos study does not anticipate changes in relative safety ranking resulting from the introduction of improved technology. The study does contain a bibliography of safety references pertaining to gaseous fuels up to 1983, many of which are not reviewed in this report.

A safety study by B.C. Research [AGP85] concluded that the survival of the gas pressure regulator in a crash is critical. The regulator is critical for retention of the fuel in a crash, but is commonly mounted at the front of the engine compartment for mounting convenience. This frontal location increases the likelihood of damage during an accident, so B.C. Research recommends mounting on the fire wall as a safer practice.

A mail survey of safety-related concerns of users and suppliers of CNG was sent to equipment suppliers, gas utilities, consumers, and government agencies. Research projects identified for priority considerations included:

- Establishing gas quality standards

- Improving methods for installing fuel tanks in vehicles

- Evaluating the performance of CNG fuel tanks during vehicle fires

- Improving methods of sealing and venting fuel tank storage compartments

- Developing methods to mitigate external corrosion of fuel tanks

- Establishment of a data base of information on accidents involving CNG vehicles.

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- Establishment of a data base of information on accidents involving CNG vehicles.

Detailed statistical treatments of the safety of CNG and LPG have not been identified, although anecdotal evidence is available regarding the safety of LPG [BPN80, Abu82] and CNG [Faw83]. An anecdotal but very convincing series of demonstrations was performed by CNG Cylinder Corp. [Faw83], in which they subjected fiberglass-reinforced aluminum cylinders to gunfire, dynamite, bonfire, and vehicle drops from a crane. TNO Road-Vehicle Research Institute in the Netherlands has conducted extensive (although not necessarily methodical) safety testing of LPG-fueled vehicles [WS80], including:

- Nine crash tests of LPG-equipped automobiles, with no tank ruptures or leakage

- Five crash tests against an LPG-equipped city bus, with no serious consequences

- Three moving barrier crash tests directly into an LPG tank mounted in front of a crash barrier, with no leaks

- Twenty-one-minute exposure to an "intense" propane fire, where the pressure relief device performed as intended and prevented uncontrolled tank leakage.

Enclosed Areas

The perception of danger has prompted bridge, tunnel, and parking garage operators to be wary of LPG. This concern is largely due to fears of poor quality conversion performed by unqualified installers [MTM82]. Although these restrictions are gradually being relaxed, particularly for factory built and certified vehicles, some restrictions still remain. A study was conducted by Ebasco Services, Inc., [GSZ89] to assess the safety of CNG vehicles when they are traveling through highway tunnels. The study combined an examination of historical accident data, analyses of gas diffusion to predict the behavior of vented gas, and a deterministic analysis to assess the consequences of a fire. The conclusion from the study is that the overall hazard of the CNG vehicle is not greater than typical gasoline vehicles.

A study by the Ontario Ministry of Transportation [Top90] has studied the issue of garaging of CNG buses, which has included a review of bus garages, accident records, and NGV bus design. Hazard identification, risk assessment, and physical modeling studies were conducted. As a result, several site modifications to existing practice were recommended: higher ventilation rates, new ventilation schemes (updraft and two-level ventilation), indirect heaters, spark-proof electrical systems, and leak detection and warning systems.

Safety Standards

Safety standards for CNG and LPG conversion kits have been established by the National Fire Protection Association (NFPA): NFPA 52 [NFPA52] for CNG and NFPA 58 for LPG (NFPA52, summarized in [SBF83]). The standards establish guidelines for the design, installation, and inspection of

- Fuel storage and dispensing systems

- Fuel tanks, including testing, inspection, and cylinder marking. For both CNG and LNG, tanks must be designed and built according to guidelines established in the American Society of Mechanical Engineers (ASME) *Boiler and Pressure Vessel Code*

- Tank location (for LPG only - NFPA58 provides LPG tank-mounting guidelines. NFPA52 is less explicit, although it does prescribe that tanks be higher than the minimum ground clearance when loaded to gross vehicle weight)

- Pressure relief devices

- Pressure gauges

- Valves

- Hose and hose connections

- Vehicle fueling connections
- Engine fuel systems
- Electrical equipment related to fueling systems.

Tank Ruptures

Because of its storage as a pressurized liquid, LPG can produce large pressure variations under very modest temperature changes. Table 18 shows the temperature-pressure relationship in a propane tank, and also the stresses in a "typical" 24-in.-diameter with a 0.187 wall thickness [HS87]. Note from the above data that even a moderate temperature of 100°C would far exceed the proof pressure of the tank.

Table 18. Variation of Tank Pressure and Stress with Temperature

Temperature		Pressure		Tank wall stress	
F	(°C)	psi	(MPa)	ksi	(MPa)
142	(47)	315	(2.17)	20	(138)
178	(67)	472	(3.26)	30	(207)
207	(83)	630	(4.35)	40	(276)
234	(98)	788	(5.44)	50	(345)
255	(110)	945	(6.52)	60	(414)
278	(122)	1100	(7.59)	70	(483)
306	(138)	1257	(8.67)	80	(552)

Proof test pressure of LPG tanks is 312 psi, and the valve safety release pressure is 250 psi. However, failure analysis of one ruptured propane tank indicates that in the case of a fire external to the tank, the safety valve may not be capable of venting gas at a sufficient rate to prevent an excessive pressure rise and tank rupture [HS87]. A worldwide search could not find a single instance of a DOT-approved cylinder failing in a CNG vehicle application [GSZ89].

Installation

As mentioned previously, a major source of safety problems is faulty installation. Leggs Products, Inc., experienced three fires from its 600 vehicle LPG fleet. The fleet manager indicates that the fires were the result of poor installation. Two of the fires occurred while the vehicles were being delivered from the conversion shop [Naf90]. Installation skill may be the most important unresolved safety issue.

Warranty Issues

The issue of vehicle warranties are a major concern for aftermarket conversions. The following excerpts illustrate typical responses to the warranty issue:

Ford Motor Company

"The installation of your product in a Ford vehicle is considered a modification of the vehicle. The installation of your Fuel System will not void the Ford new-vehicle warranty. If, however, the installation of your Fuel System causes a Ford part to fail, the cost of the repair is not covered by the Ford new-vehicle warranty. The vehicle owner would have to look to you the manufacturer or to the conversion company for repair of the modified parts as well as any related damage." [CLI91c].

Caterpillar

"The use of these conversions, in and of themselves, will not void Caterpillar's warranty. This does not imply, however, that failures which result from the use of these conversions will be covered under the Caterpillar warranty, which is limited to defects in Caterpillar's workmanship and materials for the warranty period." [CLI91c]

Cummins Engine Company, Inc.

"Cummins Engine Company neither approves nor disapproves the use of the products not manufactured or sold by Cummins Engine Company. The use of these products is left to the discretion of the end user and any failure of that product or resulting damage to the engine or performance of the engine are to be resolved by the seller and the purchaser." [CLI91c]

Technology Shortcomings

The following shortcomings of the present generation of gaseous fuel conversion kits have emerged from the present study:

Emissions - Light-duty Vehicles

- Variations in gas composition can have a pronounced impact on emissions from both CNG and LPG vehicles. Mechanical "first generation" equipment does not appear capable of maintaining adequate control of air/fuel mixture without some form of feedback.

- All of the mechanical kits being installed are subject to tampering. A common practice appears to be to "tune" for drivability instead of emissions. This may result in high HC and CO emissions.

- There are four categories of control systems for light-duty vehicles equipped with catalytic converters:

  - Fully mechanical
  - Mechanical w/O_2 feedback
  - Mechanical w/O_2 feedback and adaptive memory
  - Fully electronic w/O_2 feedback and adaptive memory.

  To date, studies have not been conducted to determine the relative effectiveness of each approach. This type of study is recommended as a priority.

- The ability of a vehicle or conversion kit to adapt to fuels of varying composition is a determining factor for in-use emissions. It is recommended that a standard test be developed for gaseous-fueled vehicles; the test would measure vehicle emissions when operating on an inventory of different standard fuels.

- Standards have not been established for testing and reporting of gaseous-fueled vehicles. This is evident from the variety of different techniques for reporting exhaust hydrocarbon levels: HC by flame ionization detector (FID) analysis, HC by gas chromatography, NMHC, CH_4, THC, NMOG, etc.

- Most CNG and LPG emissions data are from specially prepared vehicles. Although this demonstrates the potential of the fuel, it is not indicative of emissions from the in-use fleet. Data on in-use emissions of vehicles operating on CNG and LPG were not available at the time of this writing, but some data are anticipated soon.

- Virtually all converted vehicles rely on the original gasoline catalytic converter for emissions control. Although recent studies of natural gas catalysts have been conducted, the performance of gasoline catalysts when operating on CNG or LPG is not well documented.

- System integration will continue to be a major problem, even for the new electronic controllers. Primary systems integration issues include:

  - EGR control/integration
  - Canister purge
  - Knock diagnostic
  - O_2 sensor diagnostic
  - Acceleration enrichment/deceleration enleanment diagnostic.

Emissions - Medium- and Heavy-duty Vehicles

- Diesel engines are designed for in-cylinder injection. Consequently, air is used for scavenging the exhaust products. When a fumigation system is installed on a truck, a fraction of the fuel is lost in the scavenging process and shows up in the form of high HC emissions. This is particularly noticeable on two-stroke cycle engines. High HC emissions in two-stroke cycle engines also result from incomplete combustion that occurs at high A/F ratios during light loads.

- When converted to operation on gaseous fuels, particulate and NO_x levels drop but HC and CO levels increase. Some studies indicate that HC emissions from dual-fuel engines can be *extremely* high.

- Turbocharging provides an excellent means of increasing the power of gaseous-fueled engines, and to a lesser extent, the efficiency. Increased compression ratio will increase the efficiency of gaseous-fueled engines, and to a lesser extent, the power. A well-designed heavy-duty installation will probably strive for an optimal balance of both design variables. Unfortunately, these techniques are too involved for consideration as retrofit technologies.

- Catalytic converters may be required on some conversions. This can be a major obstacle (and expense) for medium- and heavy-duty vehicles (light-duty vehicles already have catalytic converters).

- Variations in A/F ratio from cylinder-to-cylinder can be a major problem for fumigated gas engines.

- Diesel pilot and lean-burn systems must currently operate open loop, which is difficult with fuels of varying composition. Lean-burn sensors appear poised for widespread use within a few years, which should help with this issue.

Safety

- Although the industry has focused on the impregnability of high-pressure tanks (both CNG and LPG), the gas lines, hoses, and valves remain the weak links in an accident.
- The quality of workmanship in the conversion has a major impact on the safety of a conversion. Currently, there are wide variations in the quality of workmanship on conversions.
- Only a few states have certification requirements for conversion equipment, although various groups are proposing industry standards.

Performance/Drivability

- Power losses on light-duty vehicles vary from the theoretical value (9.5% for methane, 4% for propane) to 20+%. Current conversion kits do not take advantage of the potential to increase power through charge air cooling.
- No systematic studies have been conducted to quantify cold starting, hot starting, or drivability. The automotive industry has developed standard tests to assess these factors on production vehicles.

Specific LPG issues

- The in-use quality of LPG at fueling stations is unknown.
- GRI provides strong and focused support for CNG activities. Although LPG has a much larger market share of the vehicular fuel market, its industry is less focused and has not been as effective in promoting new technology.

Research Needs

Below is a list of research priorities compiled for assessing the status of aftermarket fuel delivery systems and improving their capabilities:

- It is recommended that a standard test be developed for gaseous-fueled vehicles, which would measure vehicle emissions when operating on a standard set of different fuel compositions.
- A comparative study is recommended of the four types of fuel delivery equipment: fully mechanical, mechanical w/O_2 feedback, mechanical w/O_2 feedback and adaptive memory, fully electronic w/O_2 feedback and adaptive memory. This test should include emissions performance on an inventory of different fuel compositions.
- It is recommended that a standard be established for testing and reporting of emissions from gaseous-fueled vehicles. This would include guidelines for fuel composition and a standard protocol for reporting exhaust HO emissions.
- It is recommended that a comprehensive test be conducted of in-use emissions from CNG and LPG vehicles. This would involve testing of vehicles without special setup or "tuning." These tests should be conducted for light-, medium-, and heavy-duty vehicles.
- A study is recommended of the effectiveness of gasoline catalysts when operating on CNG or LPG.

- It is recommended that the use of A/F histograms be examined as an aid in evaluating the effectiveness of fuel delivery systems.

Conclusions

Both CNG and LPG have the *potential* for clean, economical, and safe operation. This is certainly true for dedicated engines. It appears that well-designed retrofit controllers, with feedback, can produce acceptable drivability and emissions when installed on light-duty vehicles. On-board diagnostics and systems integration issues (EGR, canister purge) may dictate that some vehicles will be better conversion candidates than others. The prognosis for medium- and heavy-duty conversions is more challenging. To date, the retrofit equipment for medium- and heavy-duty vehicles may involve high emissions (fumigation systems) or high cost (timed, in-cylinder injection). It is heartening to observe the development of high-quality, computer-controlled fuel delivery equipment to replace the current generation of purely mechanical equipment. A significant need exists for more high-quality equipment for diesel conversions.

Appendix A

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Appendix B
Light-duty Vehicle Emissions Data

Emissions Data - Light-Duty Vehicles

Vehicle	Literature Source	Fuel	NMHC g/mi	CH_4 g/mi	THC g/mi	CO g/mi	CO_2 g/mi	NO_x g/mi	HCHO mg/mi	MPG equiv
3.8-L Buick LeSabre[1]	[MO91]	CNG	0.051	1.287		0.757	349.5	0.603	na	na
		Indolene	0.167 FID	0.013		0.680	475.3	0.850	na	18.6
		CNG	0.037	1.526		0.300	338.1	0.580	na	na
		CNG	0.040	1.498		0.450	338.5	0.529	na	na
3.8-L Buick LeSabre[2]	[MO91]	CNG	0.084	1.43		0.167	348.7	0.362	6.94	na
		CNG	0.085	1.45		0.129	351.5	0.365	8.21	na
		CNG	0.054	1.49		0.097	349.6	0.369	5.38	na
			0.074	1.46		0.131	349.9	0.365	6.84	
3.8-L Ford Taurus[3]	[MO91]	CNG2 test avg.	0.087	1.68		0.073	376.8	1.256	6.56	na
		CNG	0.009 FID	2.09		0.090	358.0	0.699	na	na
		Indolene	0.025 FID	0.04		3.03	481.3	0.178	na	na

[1] 1989 Buick LeSabre	Bi-Fuel	CNG/Gasoline	3.8-L	Pass. Car	ANGI
[2] 1990 Buick LeSabre	Bi-Fuel	CNG/Gasoline	3.8-L	Pass. Car	ANGI
[3] 1990 Ford Taurus	Bi-Fuel	CNG/Gasoline	3.8-L	Pass. Car	ANGI

Vehicle	Literature Source	Fuel	NMHC g/mi	CH_4 g/mi	THC g/mi	CO g/mi	CO_2 g/mi	NO_x g/mi	HCHO mg/mi	MPG equiv
3.0-L Dodge Dynasty[4]	[MO91]	CNG2 test avg.	0.167	1.844		27.04	318.1	0.186	12.32	na
		CNG	0.104	1.548		15.90	315.9	0.240	5.49	na
		Methane2 test avg.	0.091	2.112		29.95	301.3	0.144	17.08	na
		Indolene	0.302	0.050		2.650	420.2	0.333	18.79	20.86
3.0-L Dodge Dynasty[5]	[MO91]	CNG3 test avg.	0.058	1.081		3.680	320.5	0.900	9.19	na
		Indolene2 test avg.	0.294	0.048		2.446	420.9	0.361	5.07	20.87
4.3-L Chevrolet Astro[6]	[MO91]	CNG2 tes avg.	0.069	2.810		0.305	435.7	0.614	13.54	na
7.5-L Ford Club Wagon[7]	[MO91]	CNG2 test avg	0.148	2.810		0.319	881.3	2.007	11.90	
5.7-L Ford F-350[8]	[MO91]	CNG	0.062	na		11.19	904	1.123	3.03	na
		Indolene	0.614 (FID)	0.266		8.70	1028	8.616	na	na
5.7-L Chev pickup w/ methane cats	unpublished	CNG			0.57	1.604	482	0.210		14.45
'81 Dual Fuel	[CARB in Kla89]	CNG	0.19			0.1		0.44		
'81 Dual Fuel	[EPA in Kla89]	gasoline	0.28			4.6		0.66		
		CNG	0.23			0.52		0.96		

4 1990 Dodge Dynasty Bi-Fuel CNG/Gasoline 3.0-L Pass. Car IMPCO

5 1990 Dodge Dynasty Bi-Fuel CNG/Gasoline 3.0-L Pass. Car IMPCO

6 1990 Chevrolet Astro Van Bi-Fuel CNG/Gasoline 4.3-L Med. Duty Trk ANGI

7 1990 Ford Club Wagon Bi-Fuel CNG/Gasoline 7.5-L Hvy Duty Trk ANGI

8 1990 Ford F-350 XLT Bi-Fuel CNG/Gasoline 5.7-L Hvy Duty Trk IMPCO

Vehicle	Literature Source	Fuel	NMHC g/mi	CH_4 g/mi	THC g/mi	CO g/mi	CO_2 g/mi	NO_x g/mi	HCHO mg/mi	MPG equiv
'72 Dual Fuel	[Kla89]	gasoline	1.2		1.4	6.3		3.7		
		CNG	0.09		0.89	1.6		1.9		
pre-'71 Dual Fuel	[Kla89]	gasoline	3.5		4.1	23		8.7		
		CNG	0.19		1.9	2.4		4.0		
Colorado State NGV	[HM91]	optim. CNG	0.06		0.63	2.5		1.33		13.7
Cal. State Northridge NGV	[HM91]	optimized CNG	0.09		0.37	4.9		0.28		10.8
Univ. of Tennessee NGV	[HM91]	optimized CNG	0.07		1.22	1.9		0.59		12.3
Florida Inst. of Tech. NGV	[HM91]	optim. CNG	0.26		1.63	39.7		0.39		11.6
Univ. of Oklahoma NGV	[HM91]	LNG	2.89		11.09	84.3		0.13		8.8
Univ. of Maryland NGV	[HM91]	LNG	5.09		14.54	149.3		0.40		9.7
Univ. of Alabama NGV	[HM91]	LNG	0.49		1.43	19.7		0.20		13.3
4.3-L S-10 pickup[9]	[Car91]	CNG	0.21		1.49	0.2		0.50		
5.7-L GMC pickup[10]	[Car91]	CNG	0.15		0.99	1.7		0.59		
3.1-L Lumina[11]	[Law91]	CNG	0.18		1.46	0.8		0.57		
		CNG, later calibration	0.15		1.22	2.9		0.25		

9 1989 GMC S10	Bi-Fuel	CNG/Gasoline	4.3-L	Lt. Duty Truck	S&S GFI
10 1989 GMC 3/4 ton pickup	Bi-Fuel	CNG/Gasoline	5.7-L	Lt. Duty Truck	S&S GFI
11 Chev. Lumina	Bi-Fuel	CNG/Gasoline	3.1-L	Pass. Car	S&S GFI

Vehicle	Literature Source	Fuel	NMHC g/mi	CH_4 g/mi	THC g/mi	CO g/mi	CO_2 g/mi	NO_x g/mi	HCHO mg/mi	MPG equiv
4.3-L S--10 pickup[12]	[Law91]	CNG	0.20		1.49	0.20		0.50		
4.3-L S-10 pickup[13]	[Lyn91]	Indolene	0.51			4.2		0.32		
	CDH 1-91	Hythane			.24	.86		.18		
	CARB 2-91	Hythane			.23	.28		.06		
5.7-L G-Van[14]	[Law91]	CNG	0.15		0.99	1.7		0.59		
5.7-L GMC pickup[15]	[Smi91]	CNG		0.12	0.48	0.7		0.16		
5.0-L Ford pickup[16]	[Dem90]	Ind. @ 7_C, 6 runs			1.62	16.80	579	1.12		
		LPG @ 4_C, 14 runs			1.20	0.04	555	0.80		
5.0-L Ford pickup First Bag Test	[Dem90]	Ind. @ 8.1_C, 6 runs			5.77	78.94	503	1.78		
		LPG @ 3.2_C, 14 runs			1.58	0.28	595	1.46		
Chev. Cheyenne[17]	[Smi91]	LPG			0.34	2.97		0.96		
'84 LPG	[Kla89]	LPG	0.27		0.32	3.0		0.39		
'81 LPG	[Kla89]	LPG	0.20		0.23	0.45		0.83		

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12 1989 GMC S10 Bi-Fuel CNG/Gasoline 4.3-L Lt. Duty Truck S&S GFI

13 1990 GMC S-10 Bi-Fuel Hythane (H_2/nat. gas) 4.3-L Lt. Duty Truck IMPCO

14 1990 GM G-Van Bi-Fuel CNG/Gasoline 5.7-L Van

15 GMC 3/4 ton pickup Unknown CNG 5.7-L Lt. Duty Truck

16 Ford F-150 pickup Bi-fuel LPG 5.0-L Lt. Duty Truck

17 Chevrolet Cheyenne Unknown LPG Unknown Lt. Duty Truck

Vehicle	Literature Source	Fuel	NMHC g/mi	CH_4 g/mi	THC g/mi	CO g/mi	CO_2 g/mi	NO_x g/mi	HCHO mg/mi	MPG equiv
pre-'71 Dual fuel LPG	[Kla89]	gasoline	3.5		4.1	23		8.7		
		LPG	1.8		2.1	3.7		3.8		
3.8-L Olds Delta 88[18]	[MO91]	LPG2 test avg	0.110	0.053		2.466	413.1	0.106	5.55	13.90 prop
		LPG	0.199	0.094		7.954	407.6	0.096	3.69	13.77 prop
		LPG	0.097	0.057		2.454	408.2	0.085	7.81	15.06 prop
		U.S. Ave[19]	0.240	0.047		3.239	463.5	0.267	2.60	18.91
2.8-L Pontiac 6000[20]	[MO91]	LPG2 test avg	0.14 (FID)	0.042		1.152	399.3	0.210	nm	14.44 prop
		Indolene	0.136 (FID)	0.037		0.908	446.5	0.287	nm	19.8
Olds Delta 88	[CARB91]	LPG4-test avg	.111	.045		2.68		.108		
Pontiac 6000	[CARB91]	LPG4-test avg	.101	.040		.72		.292		
5.0-L Ford LTD[21]	[Joh89]	LPG2 test avg			0.382	0.281	398.2	0.587	nm	nm
	[Joh89]	Indolene2 test avg			0.209	0.594	457	0.654	nm	nm

18 1989 Oldsmobile Delta 88 Bi-Fuel LPG/Gasoline 3.8-L Pass. Car IMPCO

19 U.S. Average Gasoline

20 1989 Pontiac 6000 LE Bi-Fuel LPG/Gasoline 2.8-L Pass. Car IMPCO

21 1988 Ford LTD Bi-Fuel LPG/Gasoline 5.0-L Pass. Car IMPCO

Vehicle	Literature Source	Fuel	NMHC g/mi	CH_4 g/mi	THC g/mi	CO g/mi	CO_2 g/mi	NO_x g/mi	HCHO mg/mi	MPG equiv
5.0 Ford Crown Vic[22]	[Joh90]	Indolene3 test avg			0.208	0.62	488	0.66		
		LPG2 test avg.			0.263	0.24	431	0.41		
1988 Chev. pickup[23]	[Joh90]	Gasoline2 test avg.			0.280	2.733	595	0.248		
		LPG3 test avg.			0.232	2.380	517	0.225		
5.0-L Ford LTD[24]	[EPA89]	Indolene2 test avg.	0.160		0.214	0.63	496	0.68	0.006	18.0
		LPG3 test avg	0.277		0.328	28.7	472	0.46	0.003	16.6
3.8-L Oldsmobile[25]	[ARB91]	LPG	0.064	0.057	0.122	2.453	408	0.107		14.06
2.2-L Toyota pickup[26]	[IMP91]	"Propane,"prob. LPG			0.144	2.427	367	0.262	nm	15.63

22	1988 Ford Crown Victoria	Bi-Fuel	LPG/Gasoline	5.0-L	Pass. Car	IMPCO
23	1988 Chev. 1500 Pickup	Bi-Fuel	LPG/Gasoline	5.7-L	Med. Duty Trk	IMPCO
24	1988 Ford LTD	Bi-Fuel	LPG/Gasoline	5.0-L	Pass. Car	IMPCO
25	1989 Oldsmobile		LPG/Gasoline?	3.8-L	Pass. Car	IMPCO
26	1989 Toyota Pickup		LPG/Gasoline?	2.2-L	Light Trk	IMPCO

Vehicle	Literature Source	Fuel	NMHC g/mi	CH_4 g/mi	THC g/mi	CO g/mi	CO_2 g/mi	NO_x g/mi	HCHO mg/mi	MPG equiv
2.2-L Plymouth[27]	[IMP91]	"Propane"prob. LPG			0.276	2.403	377	0.299	nm	15.2
2.2-L Plymouth[28]	[IMP91]	"Methane"prob. CNG			0.778	3.334	303	0.273	nm	18.04
2.8-L Pontiac[29]	[ARB91]	LPG	0.143	0.036	0.178	1.332	381	0.252	nm	14.30

27 1989 Plymouth K-car LPG/Gasoline? 2.2-L Pass. Car IMPCO

28 1990 Plymouth K-car CNG/Gasoline? 2.2-L Pass. Car IMPCO

29 1989 Pontiac Bi-Fuel LPG/Gasoline 2.8-L Pass. Car IMPCO

Appendix C
Heavy-duty Vehicle Emissions Data

Heavy-Duty Emissions Data

Vehicle	Literature Source	Fuel	NMHC g/hp h	THC g/hp h	CO g/hp h	PM g/hp h	NO_x g/hp h	HCHO g/hp h
New 1980-83 Bus	[EPA in Kla89]	Diesel		1.5	3.2	0.57	6.3	0.10
New 88+ DDC/Bus	[EPA in Kla89]	Diesel		0.74	1.3	0.33	5.1	
New 88+ Cummins/Bus	[EPA in Kla89]	Diesel		0.74	3.4	0.49	4.2	
New 454 Bus/no cat	[EPA in Kla89]	CNG	0.82	3.6	31.9	0.01	6.6	0.032
New 454 Bus/3w cat	[EPA in Kla89]	CNG	0.15	1.0	10.8	0.01	1.3	0.001
New 454 Bus/3w cat	[EPA in Kla89]	CNG	0.17	1.0	6.6	0.01	1.2	0.001
No control/HDT	[Sierra in Kla89]	CNG		1.6	1.3	0.02	17	
Partly Optimized/HDT	[Sierra in Kla89]	CNG		2.3	2.1		8.3	
TNO Dual Fuel/HDT	[Sierra in Kla89]	Diesel		0.34	1.6	0.40	10	
TNO Dual Fuel/HDT	[Sierra in Kla89]	CNG		16	12.6	0.25	6	
Dual Fuel/HDT	[Sierra in Kla89]	Diesel		0.9	4.4		8.5	
Dual Fuel/HDT	[Sierra in Kla89]	CNG		13.6	16		6.8	
TNO Bus w/3w Cat	[Sierra in Kla89]	LPG		1.0	7.3	0.05	1.0	
Projected Average: Diesel Uncontrolled Bus	[Sierra in Kla89]	Diesel	1.3		7.9	0.98	11.3	
Projected Average: CNG- Fumigated Bus	[Sierra in Kla89]	CNG	3.0		9.0	0.40	9.0	
Projected Average: Lean-Burn Bus	[Sierra in Kla89]	CNG	0.6		2.0	0.10	5.0	
Projected Average: Var. Mix Bus	[Sierra in Kla89]	CNG	0.4		2.5	0.10	15.0	

Vehicle	Literature Source	Fuel	NMHC g/hp h	THC g/hp h	CO g/hp h	PM g/hp h	NO_x g/hp h	HCHO g/hp h
L10 engine	[Wea89]	Diesel only		0.34	1.6	0.40	10	
		NG Fumigation		16	12.6	0.25	6	
Cat 3208	[Wea89]	Diesel only		0.9	4.4		8.5	
		NG Fumigation		12.6	15		6.8	
Ford F700 #1[1]	[FE91]	Gasoline	4.7	4.9	23.7		6.3	
		CNG	2.6	10.7	5.2		12.2	
Ford F700 #2[2]	[FE91]	Gasoline	2.9	3.2	31.0		11.0	
		CNG	1.3	4.3	15.3		11.4	
GMC C7D042 #1[3]	[FE91]	Diesel	0.6	0.6	2.8	0.70	7.0	
		Dual Fuel	5.7	39	18	0.52	8.0	
GMC C7D042 #2[4]	[FE91]	Diesel	0.6	0.6	3.0	0.76	7.5	
		Dual Fuel	7.2	24	12	0.64	7.7	

[1] 1988 Ford F700 Truck — GVW 24,500 lb — Ford 429 in^3 (7.0-L) V-8 engine rated @ 200 BHP @ 3,600 rpm on gasoline. Equipped with Allison AT-545 4-speed automatic transmission. Approximately 25,000 miles

[2] 1988 Ford F700 Truck — GVW 24,500 lb — Ford 429 in^3 (7.0-L) V-8 engine rated @ 200 BHP @ 3,600 rpm on gasoline. Equipped with Allison AT-545 4-speed automatic transmission. Approximately 25,000 miles

[3] 1986 GMC C7D042 Truck — GVW 25,600 lb — DDC 500 in^3 (8.2-L) V-8 nat. asp. engine rated @ 165 BHP @ 2,800 rpm on diesel fuel. Equipped with Allison AT-545 4-speed automatic transmission. Approximately 42,000 miles

[4] 1986 GMC C7D042 Truck — GVW 25,600 lb — DDC 500 in^3 (8.2-L) V-8 nat. asp. engine rated @ 165 BHP @ 2,800 rpm on diesel fuel. Equipped with Allison AT-545 4-speed automatic transmission. Approximately 42,000 miles

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15. Supplementary Notes

16. Abstract (Limit: 200 words)
This study evaluates the effectiveness of aftermarket fuel delivery systems for compressed natural gas (CNG) and liquefied petroleum gas (LPG). The author performed a detailed literature and product review to evaluate the performance, emissions, drivability, and safety of vehicles fueled by CNG or LPG. The study concluded that both CNG- and LPG-fueled vehicles have the potential for clean, economical, and safe operation. A list of research priorities is included.

17. Document Analysis
a. Descriptors
alternative transportation fuels, compressed natural gas, liquefied petroleum gas

b. Identifiers/Open-Ended Terms

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